CONTRACT SERIAL NO.
23440-8-9085-01-SQ

CONTRACTOR:
STELCO TECHNICAL SERVICES LTD.

STRATEGIC STUDY OF FUTURE IRONMAKING PROCESSES

VOLUME I - ANALYSIS

Final Report
by

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Work on this project was conducted under the auspices of the Department of Energy, Mines and Resources.

DSS File Number:0095Q.23440-8-9085
DSS Contract Number:23440-8-9085/01-SQ
EMR Scientific Authority:Mr. M. C. Campbell

This work was supported jointly by:

Algoma Steel Corporation
Canada Centre for Mineral and Energy Technology (CANMET)*
Canadian Carbonization Research Association (CCRA)
Canadian Liquid Air
Canadian Steel Industry Research Association (CSIRA)
Iron Ore Company of Canada, Limited
Linde Division of Union Carbide
National Slag Company
Ontario Hydro
Stelco Inc
Union Gas Company

* funding through the Federal Panel on Energy R&D (PERD)

174 pp
MICROMEDIA

92-01264/

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September 28, 1990

EXECUTIVE SUMMARY

STRATEGIC STUDY OF FUTURE IRONMAKING PROCESSES
- A CANADIAN PERSPECTIVE -

This comprehensive analysis of future ironmaking processes combines a review of the literature with the knowledge gained from interviews of Canadian coal, steel, and oxygen producers, discussions with foreign experts on this subject, and the International Symposium/Workshop on Future Ironmaking Processes, June 1990. It summarizes the present situation and trends in ironmaking processes from four aspects:

- smelting-reduction,
- blast furnace enhancements,
- coking technology, and
- coal in steelmaking.

It also considers such related aspects as direct reduction, scrap quality and availability, and environmental concerns, especially the so-called "greenhouse effect", as they affect the future ironmaking processes.

Background

We live in a time of change. Industries in Canada, in concert with those in other industrialized nations, are being challenged as never before - by lower cost competition, especially from developing nations, by mounting capital and operating costs, and by increasingly more stringent government-imposed air and water quality regulations in response to an increasingly militant, pollution-conscious public. The coal and steel industries are among the most challenged.

The blast furnace, the producer of the tonnage iron that has allowed us to reach an unprecedented standard of living, cannot operate without coke. Coke comes from coke ovens which are viewed by many as a pollution and health threat. While their view was true in the past, when less was known about the health hazards of coke chemicals and smoke was viewed with little concern, it need not be true today; the technology is available to build and operate coke ovens which are virtually environmentally friendly.

The other major drawback of coke ovens is their high cost. The industrialized countries are rapidly approaching a time when many coke ovens will expire from old age. The steel industry, squeezed for capital (increasing costs, great resistance to increased prices), may be hard pressed to replace worn-out coke oven capacity.

The blast furnace, too, is high-cost equipment and it needs to be large to be economically viable. In addition, it needs to be charged with agglomerated ore. Agglomeration adds to the cost of the hot metal and, especially in the case of sintering, has been known to add to the pollution problems of a steel plant.

With all these drawbacks in mind, researchers and process developers, especially in the industrialized nations, have for some years been working on new processes which will produce hot metal directly from coal and ore (in many cases, unagglomerated ore fines) - the smelting-reduction process. Such processes are viewed as replacements for the coke ovens/sinter plant/blast furnace route to ironmaking. Furthermore, according to their proponents, since they can be started up and shut down

easily, they are also being considered as "topping" producers of iron, i.e. to augment the blast furnace iron production of a plant in times when additional iron is required.

Canada has major producers of coal and iron ore and major manufacturers of steel. Consequently, comprehensive knowledge of technological changes in iron production is of national importance, especially since such changes could affect other industries, such as oxygen, slag, electricity, and natural gas, as well. To fully understand the impact of these potential changes on the various industries in Canada that could be affected by them, a consortium of Canadian interests (Appendix 1) commissioned a study in 1988, selecting Stelco Technical Services Limited (Steltech) as the contractor. The study, titled "Strategic Study of Future Ironmaking Processes", had the following objective:

> *To identify, analyze, and critically assess those technologies, for producing primary molten iron, which will most likely be implemented over the next 20 years - both new processes and modifications to existing processes - so as to determine their impact on the future demand for Canadian coking and thermal coals, Canadian iron ore, and various energy commodities, as well as their impact on the Canadian steel industry.*

The chief concerns of the Consortium are summarized in the following Table.

Concerns of Consortium Members

Consortium Member	Concern: the impact of technological change on:
Steel Industry	its competitive position
Coal Industry	coal markets (quantity, quality of coal)
Oxygen Companies	oxygen demand (quantity)
Ontario Hydro	electricity demand (quantity, timing)
Iron Ore Company	iron ore demand (quantity, quality, physical form)
National Slag Ltd	slag production (quantity, quality)
Union Gas Ltd	natural gas demand (quantity)
CANMET	direction of research/development in their laboratories

Current Status

Of the 22 smelting-reduction processes mentioned/described in recent literature, only a few are being pursued actively today. The front-runners are the COREX, HIsmelt, and DIOS processes. The COREX process, which operates with lump ore, or agglomerates, is commercial (a 300 000 tpa plant at ISCOR, South Africa). The HIsmelt and DIOS processes, which use unagglomerated ore fines, are just now entering the major pilot plant/demonstration plant stage. The North American contender, the AISI Direct Steelmaking process, has just entered the small pilot plant stage.

Considerable effort is under way towards decreasing the quantity of coke required in the blast furnace process. The major effort in Europe and Japan seems to evolve around coal injection. Operating injection rates of up to 140 kg/thm have been achieved, with successful tests up to 170 to 180 kg/thm. In Russia, combined blast, i.e. high levels of natural gas injection with high levels of oxygen enrichment of the hot blast, has been standard practice on numerous blast furnaces for years; testing is under way in the USA.

Germany seems to be the only industrialized nation to have in place a coke ovens modernization program. Ruhrkohle AG and Bergbauforschung are in the forefront of coking developments, with wide coke ovens and the development of the Jumbo Coking Reactor under way. The Japanese national initiative to develop a formed coke process has been completed, but so far no company has announced plans to apply this technology. Another Japanese national initiative, this one to develop a new coking process, seems to be taking shape.

The designation "coal in steelmaking" covers a wide range of processes. Of the 11 processes reported in the literature, the four which would be most likely to affect the Canadian situation are the KMS/KS process, NSC's New Melting process, the K-ES process, and the EOF process.

The KMS/KS process is commercial. It provides for the injection of coal into a K-OBM to increase the percentage of scrap in the charge, i.e. it decreases the dependency upon hot metal. NSC's New Melting process was developed to enable NSC to shut down one blast furnace at each of two plants. It is a 100 percent scrap-based process utilizing existing BOFs. It seems to be one embodiment of KS technology. It was to have been commercial by now but, because of an unanticipated demand for hot metal, the blast furnaces are still operating. The K-ES process is commercial in two plants in Italy; it substitutes a primary source of energy, coal, for a portion of the electrical energy. The EOF is commercial at two plants in Brazil (and possibly one in India). It operates on a mixture of hot metal and scrap and was developed to replace open hearth furnaces in Brazil. It can also operate on 100 percent scrap.

Future Trends

In Canada, as in the other industrialized nations, the blast furnace will continue to predominate as the major tonnage-iron producer well into the next century, but with decreasing reliance on coke. Coal injection will begin in Canada as coke ovens are shut down and, elsewhere, will be practiced on more blast furnaces. On those furnaces already injecting coal, it will become more intensive; the next operating level of coal injection will be 160 kg/thm and the one beyond that will be 200 kg/thm. Canadian blast furnace operations are expected to follow this same pattern with decreasing coke plant capacity. As coal injection rates are increased above 100 kg/thm, oxygen enrichment of the hot blast will have to be increased accordingly.

Coal injection will also change the coal market, since more coal suppliers can compete to sell injection coal when the overriding criterion is price. The market for metallurgical coal, a big export market for Canadian coal producers, will become more competitive as it shrinks.

Coke ovens will have to be built or rebuilt to supply the coke to the blast furnaces - in Canada and elsewhere. However, the individual oven size is expected to increase, especially in width. This, along with the lower coke requirement resulting from coal injection, will result in significantly fewer ovens producing the coke required for a given ironmaking capacity.

A growth in merchant coke production is a distinct possibility; Australian coke is already being exported to the east coast of the USA. Merchant coke may have to come from outside Canada, however; little enthusiasm to produce merchant coke was evident during discussions with Canadian company officials.

Iron ore pellets will continue to be needed to feed the blast furnaces. The COREX process also represents a market for pellets. Canadian specular hematite concentrate may eventually find a market in the HIsmelt and DIOS processes, but this market is unlikely to develop within the next 20 years.

Higher natural gas injection rates may find application as an interim measure to replace coke; it has the added advantage of decreasing the CO_2 emitted during blast furnace ironmaking. In the long run, well before 2010, it will become too expensive for this application.

Smelting-reduction processes, even COREX which is essentially commercial, are expected to make no significant inroads against blast furnace ironmaking until after 2010, possibly much after.

By the turn of the century, the HIsmelt and DIOS processes are expected to be operational in their first small commercial plants. The initial major applications of these two processes, and COREX, may very well be as a supplier of hot metal (virgin iron units) to minimills. At this time, however, the probability of any of these processes being adopted in Canada by 2010 appears to be very low.

The use of coal in steelmaking will become more widespread, especially via the K-ES and EOF processes. These processes may see some application in Canada, if the economics warrant it, but are more likely to be applied elsewhere. The KMS/KS process may have some application in some plants but is unlikely to enjoy widespread use; NSC's New Melting process is in the same category. Neither is expected to be adopted in Canada.

Scrap will still be needed by the steel producers and seems to be in adequate supply. Scrap supply, however, could be adversely affected if the fluff problem arising from automobile shredding is not resolved quickly.

Those minimill operators who want to enter the higher-value products markets, and especially the quality flat rolled products market, may have to consider using a source of virgin iron to dilute the residuals in the scrap. One major option, besides the product of smelting-reduction, is direct reduced iron. Direct reduction is enjoying an upsurge in Venezuela, and the merchant hot briquetted iron produced there is being targeted towards the North American market to be used as a "sweetener" in scrap-based steelmaking.

Tonnage iron production must be based on carbon reduction; no other fuel/reductant is economically viable. The by-product, of course, is carbon dioxide, the most prevalent of the "greenhouse" gases. Coal-fired power generation is responsible for only about eight percent of the man-made greenhouse gas emissions worldwide (1986); the contribution from blast furnace ironmaking is considerably less than that. The coal, steel, and electricity-producing industries have a responsibility to become as energy-efficient as possible, and thereby minimize their contribution to the "greenhouse effect", but they must not become the scapegoats for this current perceived problem. An increase in the hydrogen content of the energy these industries consume, as for example by the substitution of natural gas for coal and/or coke where it is economically viable, would also be advantageous in reducing carbon dioxide emissions.

The Next Step

Millions of dollars are being spent worldwide on developing new ironmaking processes. Canadian industry does well to not compete in this costly activity. However, much can be done in this country; we have the expertise and the will, we just don't have the size.

Several concerns were uncovered during the course of this study which should be addressed. These include the following:

- the disposal/utilization of the fluff generated in the shredding of automobiles, etc,
- design for recycling - automobiles and other mobile equipment, appliances, etc,
- efficiency-improving combustion technologies, including how to maximize coal injection through the tuyeres of the blast furnace,

- nonrecovery coke ovens with electricity co-generation,
- potential of, and potential locations for, merchant coke ovens,
- adequate, completely honest, public relations on behalf of coal and its consumption,
- the adequacy and reliability of the data upon which decisions will be made regarding the "greenhouse effect" and controls/penalties re the emission of greenhouse gases, especially CO_2, and
- energy conservation/substitution from the aspect of decreasing the release of CO_2 into the atmosphere.

This list is not exhaustive, nor is it in order of priority, but it could form a base for discussions at the follow-up meeting to be called by EMR to determine the actions which should stem from this report.

SOMMAIRE EXÉCUTIF

ÉTUDE STRATÉGIQUE DES FUTURS PROCÉDÉS D'ÉLABORATION DE L'ACIER

- PERSPECTIVES CANADIENNES -

Cette analyse globale des futurs procédés d'élaboration combine un examen des publications spécialisées avec l'information recueillie à l'occasion d'entrevues avec des producteurs canadiens de charbon, d'acier et d'oxygène, et à l'occasion de discussions avec des experts étrangers en la matière, et l'information diffusée à l'occasion du symposium international sur les futurs procédés d'élaboration de l'acier tenu en juin 1990. Cet article constitue un sommaire de la situation actuelle et des tendances affectant les procédés d'élaboration de l'acier, sous quatre aspects:

- fusion-réduction,
- amélioration des hauts fourneaux,
- technologie de cokéfaction, et
- emploi du charbon pour l'élaboration de l'acier.

Dans cette analyse, on considère également des aspects connexes comme la réduction directe, la qualité et la disponibilité des ferrailles et les facteurs affectant l'environnement, particulièrement l'effet de serre, en ce qui concerne leur influence sur les futurs procédés d'élaboration de l'acier.

Antécédents

Nous traversons une période de changement. Les industries canadiennes, de concert avec celles des autres nations industrialisées, affrontent des défis plus que jamais auparavant - concurrence des producteurs à bas prix, particulièrement des pays en voie de développement, augmentation des coûts d'investissement et des frais d'exploitation, et imposition de réglementations de plus en plus rigoureuses par les gouvernements à l'égard de la qualité de l'air et de l'eau en réaction au comportement de plus en plus militant d'un public qui prend conscience de la pollution. Les industries de production de charbon et d'acier figurent parmi celles qui affrontent les défis les plus importants.

Le haut fourneau, l'équipement de production de grand tonnage de fonte qui nous a permis d'atteindre un niveau de vie sans précédent, ne peut fonctionner sans coke. Le coke provient de fours à coke, que beaucoup considèrent comme d'importantes sources de pollution et de menace pour la santé. Tandis que ce point de vue était valide dans le passé, lorsqu'on connaissait moins de choses au sujet des risques pour la santé des produits chimiques associés au coke et qu'on se souciait peu de la fumée, ceci n'est plus nécessairement vrai aujourd'hui; il existe maintenant des technologies qui permettent la construction et l'exploitation de fours à coke virtuellement sans danger pour l'environnement.

L'autre désavantage important des fours à coke est leur coût élevé. Les pays industrialisés approchent rapidement de l'époque à laquelle de nombreux fours à coke disparaîtront par raison de vieillesse. L'industrie de l'acier, pauvre en capital (augmentation des coûts, grande résistance aux augmentations de prix), pourrait avoir des difficultés à remplacer la capacité de production de coke qui disparaîtra ainsi.

Le haut fourneau est également un équipement à coût élevé et il faut qu'il soit de grande taille pour qu'il puisse être économiquement viable. De plus, on doit le charger de minerai aggloméré. L'opération d'agglomération augmente le coût du métal liquide primaire produit, et particulièrement dans le cas du frittage, cette opération augmente encore les problèmes de pollution d'une aciérie.

Compte tenu de tous ces désavantages, les chercheurs et spécialistes des procédés, particulièrement dans les pays industrialisés, ont travaillé pendant plusieurs années sur de nouveaux procédés qui permettraient la production directe de métal liquide primaire à partir de charbon et de minerai (dans de nombreux cas, de minerai pulvérulent, non aggloméré) - le procédé de fusion-réduction. On considère que de tels procédés pourraient remplacer la voie four à coke/installation d'agglomération/haut fourneau dans l'élaboration de l'acier. De plus, selon leurs promoteurs, comme on pourrait facilement les mettre en marche et les arrêter, on pourrait les utiliser également comme unités de production d'appoint de fonte c. à d. pour augmenter la production de fonte des hauts fourneaux lorsqu'une demande additionnelle se manifeste.

Le Canada possède plusieurs importants producteurs de charbon et de minerai de fer, et d'importants producteurs d'acier. De ce fait, une connaissance complète de l'évolution technologique de la production d'acier est d'importance nationale, particulièrement parce que de tels changements pourraient affecter également d'autres industries, comme les industries de production d'oxygène, de scorie, d'électricité et de gaz naturel. Un consortium d'intérêts canadiens (Annexe 1) a commandité en 1988 une étude qui fut exécutée par Stelco Technical Services Limited (Steltech) pour comprendre totalement l'impact de ces modifications potentielles sur les diverses industries canadiennes qu'elles pourraient affecter. Le rapport de cette étude intitulé Strategic Study of Future Ironmaking Processes (Étude stratégique des futurs procédés d'élaboration de l'acier) avait l'objectif suivant:

> *Identifier, analyser, et évaluer de manière critique les technologies de production de métal liquide primaire dont la probabilité de mise en oeuvre au cours des 20 prochaines années est élevée - à la fois nouveaux procédés et modifications de procédés existants - afin qu'il soit possible de déterminer leur impact sur la demande future de charbon thermique et de charbon cokéfiable canadiens, de minerai de fer canadien, et de diverses sources d'énergie, ainsi que leur impact sur l'industrie canadienne de production d'acier.*

Le tableau suivant résume les principales préoccupations du Consortium.

Préoccupations des membres du Consortium

Membre du Consortium	Préoccupation: L'impact des modifications technologiques sur:
Industrie de production d'acier	sa position concurrentielle
Industrie du charbon	les marchés du charbon (quantité, qualité du charbon)
Compagnies de production d'oxygène	demande d'oxygène (quantité)
Ontario Hydro	demande d'électricité (quantité, distribution dans le temps)
Iron Ore Company	demande de minerai de fer (quantité, qualité, forme physique)
National Slag Ltd	production de scorie (quantité, qualité)
Union Gas Ltd	demande de gaz naturel (quantité)
CANMET	orientation des activités de recherche et développement dans leurs laboratoires

Situation actuelle

Parmi les 22 procédés de fusion-réduction mentionnés et décrits dans les publications récentes, seulement quelques-uns font encore l'objet de travaux actifs aujourd'hui. Les favoris sont les procédés COREX, HIsmelt, et DIOS. Le procédé COREX, qui utilise du minerai grossier ou des agglomérés, est utilisé commercialement (une usine de 300 000 tonnes par an à ISCOR, en Afrique du Sud). Les procédés HIsmelt et DIOS, qui utilisent un minerai pulvérulent non aggloméré ne font qu'accéder à l'étape usine pilote importante/démonstration. Le procédé originaire d'Amérique du Nord, procédé d'élaboration directe AISI, vient seulement d'atteindre l'étape de la petite usine pilote.

Des efforts considérables sont déployés dans les travaux en cours ayant pour objectif une réduction de la quantité de coke nécessaire à un haut fourneau. Les principales techniques étudiées en Europe et au Japon semblent concerner l'injection de charbon. Des taux d'injection de charbon jusqu'à 140 kg/tf ont été obtenus dans les conditions d'exploitation et des tests ont été réussis jusqu'à 170 à 180 kg/tf. En URSS, l'emploi d'un vent combiné c. à d. l'injection de grandes quantités de gaz naturel en conjonction avec un fort enrichissement à l'oxygène dans le vent chaud du haut fourneau est la technique standard couramment utilisée sur de nombreux hauts fourneaux depuis des années. Des essais à ce sujet sont en cours aux É.-U.

L'Allemagne semble être le seul pays industrialisé qui s'intéresse à un programme de modernisation des fours à coke. Ruhrkohle AG et Bergbauforschung sont à l'avant-garde des développements dans le domaine de la cokéfaction; la construction d'un four à coke large et la mise au point du réacteur de cokéfaction Jumbo sont en cours. Les travaux de l'initiative nationale japonaise de mise au point d'un procédé de production de coke formé ont été complétés, mais jusqu'à présent la compagnie n'a pas annoncé l'intention d'appliquer cette technologie. Une autre initiative nationale japonaise, celle-ci ayant pour objet la mise au point d'un nouveau procédé de cokéfaction, semble prendre forme.

Le sujet "utilisation du charbon dans l'élaboration de l'acier" couvre une grande gamme des procédés. Parmi les 11 procédés mentionnés dans les publications, les quatre procédés qui auraient la plus forte probabilité d'affecter la situation canadienne sont les suivants: procédé KMS/KS, nouveau procédé de fusion NSC, procédé K-ES, et procédé EOF.

Le procédé KMS/KS est utilisé commercialement. Il implique l'injection de charbon dans un four K-OBM, ce qui permet l'augmentation du pourcentage de ferraille dans la charge, c. à d. qu'il réduit le besoin de métal liquide primaire. NSC a mis au point le nouveau procédé de fusion NSC afin de pouvoir arrêter un haut fourneau dans chacune de deux usines. Il s'agit d'un procédé basé à 100 pour cent sur la ferraille, utilisant des fours à oxygène (BOF) existants. Il semble incorporer la technologie KS. Il était prévu qu'il soit maintenant utilisé commercialement, mais du fait d'un niveau imprévu de demande de métal liquide primaire, les hauts fourneaux sont encore en exploitation. Le procédé K-ES est utilisé commercialement dans deux usines en Italie; il implique le remplacement d'une certaine quantité d'énergie électrique par une source d'énergie primaire, le charbon. Le procédé EOF est utilisé commercialement dans deux usines brésiliennes (et peut-être dans une usine en Inde). Il implique l'emploi d'un mélange de métal liquide primaire et de ferraille; il a été mis au point afin qu'il puisse remplacer les fours Martin au Brésil. Il peut être également alimenté à 100 pour cent de ferraille.

Tendances futures

Au Canada comme dans les autres nations industrialisées, le haut fourneau demeurera l'équipement prédominant de production de fonte en tonnage élevé pendant de nombreuses années au siècle prochain, mais en utilisant moins de coke. La technique d'injection de charbon commencera à être utilisée au Canada à mesure de la fermeture des fours à coke, et ailleurs elle sera utilisée sur un plus grand nombre de hauts fourneaux. Cette technique sera utilisée de plus en plus intensément sur les

fourneaux sur lesquels on emploie déjà l'injection de charbon; le prochain palier du taux d'injection de charbon dans les conditions d'exploitation sera de 160 kg/tf et le niveau suivant sera de 200 kg/tf. On prévoit que les entreprises canadiennes utilisant des hauts fourneaux connaîtront une évolution similaire à mesure de la réduction de la capacité des usines de production de coke. À mesure que les taux d'injection de charbon augmenteront au-delà de 100 kg/tf, il sera nécessaire d'augmenter de pair l'enrichissement à l'oxygène du vent chaud injecté dans les hauts fourneaux.

L'emploi de la technique d'injection de charbon suscitera également des modifications du marché du charbon, car un plus grand nombre de fournisseurs de charbon peuvent se faire concurrence et tenter de vendre du charbon d'injection lorsque le principal critère est celui du prix. Le marché du charbon métallurgique, qui constitue un important marché d'exportation pour les producteurs de charbon canadiens, deviendra plus concurrentiel à mesure qu'il se contractera.

Des fours à coke devront être construits et reconstruits pour qu'ils puissent satisfaire la demande de coke des hauts fourneaux - au Canada et ailleurs. Cependant, on prévoit une augmentation de la taille des fours, particulièrement de leur largeur. Ceci, conjointement avec la réduction de la consommation de coke due à l'emploi de l'injection de charbon, permettra à un nombre de fours sensiblement moins élevé de produire le coke nécessaire pour une capacité de production donnée.

Il est également très possible qu'on enregistre une croissance de la production de coke destinée à la vente commerciale; le coke australien est déjà exporté vers la côte Est des É.-U. Cependant, il se peut qu'il soit nécessaire que ce coke du marché commercial provienne de l'extérieur du Canada; au cours des discussions avec les dirigeants des compagnies canadiennes, on a enregistré peu d'enthousiasme pour une production commerciale de coke.

La disponibilité de minerai de fer en boulettes agglomérées demeurera nécessaire, pour l'alimentation des hauts fourneaux. Le procédé COREX constitue également un marché pour ces boulettes de minerai agglomérées. Le concentré canadien d'hématite spéculaire pourrait finalement trouver un marché dans les procédés HIsmelt et DIOS, mais il est improbable que ce marché se développe au cours des 20 prochaines années.

L'empoi de taux d'injection de gaz naturel plus élevé pourrait remplacer le coke, à titre de mesure intérimaire; ceci susciterait l'avantage additionnel d'une réduction du volume de CO_2 émis lors de la production de fonte au haut fourneau. À long terme, bien avant l'an 2010, le coût du gaz naturel deviendra trop élevé pour ces applications.

On ne prévoit pas que les procédés de fusion réductrice même le procédé COREX qui a essentiellement atteint le niveau commercial, accaparent une fraction significative de la production annuelle des hauts fourneaux avant l'an 2010, et peut-être beaucoup plus tard.

D'ici la fin de ce siècle, les procédés HIsmelt et DIOS pourraient être opérationnels dans leurs premières petites usines commerciales. La première application importante de ces deux procédés et du procédé COREX pourrait bien être la production de métal liquide primaire, élaboré à partir d'un minerai vierge, à l'intention des mini-aciéries. Cependant, on considère actuellement que la probabilité que l'un de ces procédés soit adopté au Canada avant l'an 2010, est très faible.

L'emploi du charbon dans l'élaboration de l'acier se développera, particulièrement dans le cadre des procédés K-ES et EOF. Ces procédés pourraient trouver quelques applications au Canada si cela est justifié par les conditions économiques, mais il est plus probable qu'ils soient utilisés ailleurs. Le procédé KMS/KS pourrait avoir certaines applications dans quelques usines, mais il est improbable qu'il se répande beaucoup; il en est de même pour le nouveau procédé de fusion NSC. On ne prévoit pas qu'un de ces procédés soit adopté au Canada.

Les producteurs d'acier auront encore besoin de ferraille, et il semble qu'elle soit disponible en quantité adéquate. Cependant, la disponibilité de ferraille pourrait être négativement affectée si le

problème du volume de matériaux légers non métalliques provenant du déchiquetage des automobiles n'est pas rapidement résolu.

Les exploitants de mini-aciéries qui désirent accéder au marché des produits à forte valeur ajoutée, et particulièrement au marché des produits plats laminés de qualité, pourraient être obligés de considérer l'emploi d'une source de minerai vierge pour le dilution des impuretés résiduelles provenant de la ferraille. À part l'emploi de produits du procédé de fusion-réduction, l'emploi de fer produit par réduction directe pourrait être une importante option. Le procédé de réduction directe connaît un regain de faveur au Venezuela, et le fer en briquettes qui y est produit fait maintenant l'objet d'activités de promotion commerciale sur les marchés nord américains où il pourrait être utilisé comme élément "adoucisseur" dans les aciéries basées sur l'emploi de ferraille.

La production d'acier en tonnage élevé doit être basée sur la réduction par le carbone; l'emploi d'aucun autre combustible réducteur n'est économiquement viable. Le sous-produit est bien sûr le dioxyde de carbone, le plus répandu des gaz qui contribuent à l'effet de serre. La génération d'électricité dans les centrales au charbon n'est responsable que d'environ huit pour cent des émissions mondiales de gaz (1986), générés par l'homme et qui contribuent à l'effet de serre; la contribution imputable à la production d'acier et aux hauts fourneaux est considérablement moins élevée. Il incombe aux industries de production de charbon, de production d'acier et de production d'électricité la responsabilité qu'elles deviennent aussi efficaces que possible quant à leur consommation d'énergie, et qu'elles minimisent ainsi leur contribution à l'effet de serre, mais il ne faut pas qu'elles deviennent les boucs émissaires des problèmes actuellement perçus. Une augmentation de la contribution de l'hydrogène dans la consommation d'énergie de ces industries, par exemple, par la substitution de gaz naturel au charbon et/ou coke lorsque cela est économiquement viable, conduirait également à une réduction avantageuse des émissions de dioxyde de carbone.

L'étape suivante

On dépense des millions de dollars dans le monde entier à la mise au point de nouveaux procédés d'élaboration de l'acier. La décision de l'industrie canadienne de ne pas participer à la concurrence dans ces coûteuses activités est judicieuse. Cependant, on peut faire beaucoup dans ce pays; nous possédons l'expertise et la volonté; il ne nous manque que la taille.

Plusieurs sources de préoccupation ont été identifiées dans le cadre de cette étude, lesquelles devraient être étudiées. Il s'agit des suivantes:

- élimination/utilisation des matières non-métalliques et volumineuses générées lors du déchiquetage des automobiles, etc,
- conception des automobiles et autres équipements mobiles, appareils ménagers, etc, en vue du recyclage,
- technologie de combustion améliorant l'efficacité; ceci devrait inclure la recherche de la maximisation des injections de charbon à travers les tuyères des hauts fourneaux,
- fours à coke sans récupération, avec co-génération d'électricité,
- potentiel de production de coke pour la vente commerciale, et sites potentiels d'établissement de telles installations,
- activités de relations publiques adéquates et totalement honnêtes au sujet du charbon et de sa consommation,
- suffisance et fiabilité des données sur lesquelles les décisions seront fondées en ce qui concerne l'effet de serre, et contrôle/pénalité quant aux émissions des gaz contribuant à l'effet de serre, particulièrement le CO_2, et
- conservation/substitution de l'énergie quant à la réduction de l'émission de CO_2 dans l'atmosphère.

Cette liste n'est pas exhaustive, et elle n'est pas présentée non plus dans l'ordre des priorités, mais elle pourrait constituer une base de discussion pour une réunion de suivi organisée à la demande du ministère de l'Énergie, des Mines et des Ressources, en vue de la détermination des initiatives qui pourrait découler de ce rapport.

TABLE OF CONTENTS

- VOLUME I -

EXECUTIVE SUMMARY i

SOMMAIRE EXÉCUTIF vi

INTRODUCTION 1

SUMMARY TO 2010 3

RECOMMENDATIONS 5

SMELTING-REDUCTION 6
- COREX Process 8
- HIsmelt Process 21
- Direct Iron Ore Smelting (DIOS) Process 29
- AISI Direct Steelmaking Process 36

BLAST FURNACE ENHANCEMENTS 43
- Coal Injection 45
- Combined Blast 55

COKING TECHNOLOGY 57
- Current Coke Ovens 59
- Jumbo Coking Reactor 63
- Formed Coke 67

COAL IN STEELMAKING 76
- KMS/KS Process 78
- NSC's New Melting Process 84
- K-ES Process 86
- Energy Optimizing Furnace (EOF) 91

RELATED CONSIDERATIONS 99
- Scrap Quality and Availability 100
- Direct Reduction 106
- Coal Outlook 109
- "Greenhouse Effect" 117

IMPACT 127

REFERENCES 144

ACKNOWLEDGEMENT 152

APPENDIX 1 - STRATEGIC STUDY CONSORTIUM

APPENDIX 2 - VISITS TO CANADIAN COMPANIES

APPENDIX 3 - VISITS TO INTERNATIONAL EXPERTS

INTRODUCTION

Substantial research effort is being expended internationally to improve the production of molten iron for steelmaking. Developments are being pursued actively on two fronts, improvements to existing facilities and processes and replacement of those processes. In both cases, the primary objective is the same - to overcome the high costs associated with cokemaking, while eliminating or reducing the environmental problems which occur within integrated steelmaking complexes.

Improvements to existing facilities and processes are focused on both the coke ovens and the blast furnace. Coke oven builders are testing new coke oven designs to reduce capital cost and eliminate environmental and health concerns arising from the coking process. For their part, blast furnace operators are studying or adopting technologies which significantly reduce the blast furnace's reliance on metallurgical coke, e.g. coal injection and oxygen enrichment, plasma technology, etc. This two-pronged approach has the potential to provide an improved ironmaking system, based on the traditional approach of coke ovens/blast furnace, which minimizes the problems associated with the manufacture of coke.

Replacement of the coke ovens/blast furnace route to ironmaking is being pursued through the development of new processes which produce molten iron without the need for metallurgical coke. Almost all of these processes are coal-based and use large volumes of pure oxygen. Within this group of processes, there exist several subgroups, for example, processes based on iron ore fines to avoid agglomeration; two-step processes for reduction and melting; and single-step converter processes. Replacement and/or partial replacement of the coke ovens/blast furnace route as the basis for steelmaking is also being pursued through the use of coal injected directly into BOF-type vessels and electric arc furnaces. The addition of this auxiliary energy increases the percentage of scrap which can be used in the BOF, even up to 100 percent, decreasing its dependence upon hot metal from the blast furnace and, hence, the need for coke. In the electric arc furnace, the injection of primary energy such as coal reduces the consumption of costly electric power and electrodes.

Improvements to blast furnace and coke oven technologies are being developed worldwide, with major efforts in Europe and Japan. Replacement technologies, including the direct use of coal in steelmaking, are also being developed worldwide. Pilot or demonstration-scale ironmaking projects are ongoing in Japan, the United Kingdom, France, West Germany, the Netherlands, Sweden, Australia, and the United States. These processes are being developed both by private industry and with government financial support. The intensity of technological activity indicates a strong likelihood that changes in ironmaking technology will be commercialized over the next 20 years.

Canada has major producers of coal and iron ore and major manufacturers of steel. Consequently, comprehensive knowledge of technological changes in iron production is of national importance. To fully understand the impact of these potential changes on the various industries in Canada that could be affected by them, a consortium of Canadian interests (Appendix 1) commissioned a study in 1988, selecting Stelco Technical Services Limited (Steltech) as the contractor to carry it out. The study, titled "Strategic Study of Future Ironmaking Processes", had the following objective:

> *To identify, analyze, and critically assess those technologies, for producing primary molten iron, which will most likely be implemented over the next 20 years - both new processes and modifications to existing processes - so as to determine their impact on the future demand for Canadian coking and thermal coals, Canadian iron ore, and various energy commodities, as well as their impact on the Canadian steel industry.*

To understand the expectations and needs of the consortium members with respect to this study, visits were undertaken to a number of the companies involved (Appendix 2).

This report combines what the literature searching revealed and the updated information which was obtained through visits to international experts (Appendix 3) and at the International Symposium/Workshop on Future Ironmaking Processes held in Hamilton, Ontario, Canada, June 14 and 15, 1990, as part of Steltech's contractual obligations. It is in two volumes.

Volume I summarizes the present situation and trends in ironmaking processes from four aspects:

- smelting-reduction,
- blast furnace enhancements,
- coking technology, and
- coal in steelmaking.

It also considers such related aspects as direct reduction, scrap quality and availability, and environmental concerns, especially the so-called "greenhouse effect", as they affect the future ironmaking processes. Because of the length and complexity of the main body of the report, the "Summary to 2010", which summarizes the findings of this project, and the "Recommendations" follow immediately.

Volume II contains a concise description of each of the pertinent processes indicating its developer, its objective, its basic principles, its current status, potential contacts, and references.

SUMMARY TO 2010

1. In Canada, as well as elsewhere, the blast furnace will continue to be the primary producer of molten iron, but with decreasing dependency on coke. Smelting-reduction processes are expected to make no significant inroads against the blast furnace until at least beyond the year 2010.

2. While other technologies are being developed to decrease the blast furnace's dependency on coke, coal injection through the tuyeres will be the main technology employed for this purpose. More blast furnaces will inject coal, and injection rates will increase from the current nominal ~100 kg/thm to 200 kg/thm (or beyond).

3. Increasing rates of coal injection in the blast furnace will significantly increase oxygen demand. Oxygen enrichment starts to be needed at injection rates of about 100 kg/thm and must be increased, essentially proportionately, as the coal injection rate is increased.

4. Increased demand for oxygen to enrich the hot blast will create an additional demand for electric power generation.

5. Canada's coal producers may face a significant decrease in demand for coking coal, which could be offset to some extent by increasing markets for injection coal. However, the competition will be greater because more latitude exists in the specifications for injection coal, which could significantly increase the number of potential suppliers. Another drawback of the injection coal market is that the most important specification seems to be low price.

6. Canadian coal producers will face strong competition not only from traditional competitors, such as Australia and South Africa, but also from additional competitor countries such as Colombia. Furthermore, the Japanese, who represent a major market, are expected to continue their quest for lower-cost raw materials.

7. Iron ore pellets will still be needed to feed the blast furnaces. Thus, Canada's iron ore producers, provided they remain competitive, should retain their markets. The COREX process is also a candidate to process good pellets; processes such as HIsmelt and DIOS might do well on coarse, high-grade, specular hematite concentrate.

8. No change in blast furnace slag quality or quantity is anticipated in Canada over the next 20 years. Should the COREX process be installed in Canada, it will produce slag comparable to blast furnace slag.

9. The COREX, K-ES, and EOF processes will all demand significant increases in oxygen supply, depending on how widespread their use becomes. On their own, the increased oxygen demand would signal a consequent increase in electric power demands. However, if they displace EAF capacity, the "released" electric power should be more than enough to generate the required oxygen.

10. Scrap supplies are expected to be adequate, with the possible exception of low residuals scrap. This high grade scrap could escalate in price if demand for it escalates. The alternative is to use a lower grade (higher residuals content) scrap and add a diluent.

11. Commonly used diluents for scrap residuals include pig iron, fragmented iron, direct reduced iron (DRI), hot briquetted iron (HBI) and blast furnace hot metal. Other processes coming on-stream add to the choices, e.g. hot metal from smelting-reduction processes and solid iron carbide.

12. Direct reduced iron is enjoying a resurgence in Venezuela. The merchant HBI and the briquetted DRI being produced there are targeted mainly to the North American market.

13. Tonnage iron production must be based on carbon reduction; no other fuel/reductant is economically viable. Carbon dioxide (CO_2), the most prevalent of the "greenhouse" gases, is the inevitable by-product of coal-based ironmaking. Well-meaning but uninformed legislation could do irreparable harm to the industry.

14. Coal-fired power generation is responsible for only about eight percent of the man-made greenhouse gas emissions worldwide (1986); the contribution from blast furnace ironmaking is considerably less than that. While the coal, steel and electricity-producing industries have a responsibility to become as energy-efficient as possible, and thereby minimize their contribution to the "greenhouse effect", they must not become the scapegoats for this perceived problem.

RECOMMENDATIONS

1. Canadian industries should consider carefully the information in this report in developing short-term and strategic plans. Each company is unique and the technology and/or situation which applies to one company may not apply to another but this report should assist greatly in crystallizing technological direction.

2. Canadian industries should keep themselves thoroughly apprised of smelting-reduction process development, new coke oven designs, and ultra-high levels of coal injection/oxygen enrichment in the blast furnace for earliest adoption opportunities.

3. The steel industry, especially those plants operating electric arc furnaces, would do well to follow closely the relevant technologies described in this report, including the use of HBI, so as to not fall behind competitors.

4. The coal producing and consuming industries should establish and maintain excellent contacts with elected government officials and bureaucrats to ensure sound input to government decisions on the future use of coal.

5. Canadian industries, cooperatively with EMR, should undertake to develop, promote, and establish design for recycling - to minimize waste production and the cost and difficulty of its disposal, e.g. fluff from automobile shredders.

6. EMR should host a meeting, in mid November, 1990, of representatives of the consortium which financed this study, plus other invited representatives of the ferrous metallurgy community, to decide where to go from here collectively and the role that each should play.

7. This report should be updated at intervals no greater than every five years.

SMELTING-REDUCTION

Over the years, numerous attempts have been made to develop a viable smelting-reduction process. Some processes met with a measure of success; others merely failed - for one reason or another. In studying the literature, we noted the 22 processes listed in Table I (and described briefly in Volume II).

Table I: Smelting-Reduction Processes

Process	Developer
Coal Iron Gasification Process (CIG)	Japan/Sweden joint feasibility study for International Energy Agency
Converted Blast Furnace (CBF)	British Steel Corp/Hoogovens
Coal Oxygen Injection Process (COIN)	Fried Krupp Research Institute
Combismelt	Lurgi/Mannesmann-Demag Huttentechnik
COREX	Korf Engineering/Voest-Alpine
Davy McKee	Davy McKee Research and Development
DIOS (NKK)*	Nippon Kokan KK/JISF
Elkem Polar	Elkem Technology
Elred	Stora Kopparberg Bergslag AB/ASEA/Lurgi
Foster Wheeler-Tetronix	Foster Wheeler/Tetronix
HIsmelt	CRA Ltd/(Klöckner Stahlwerke)/Midrex Corp
Inred	The Boliden Group of Companies
KHD	KHD Humboldt Wedag AG
Kobe	Kobe Steel Company Ltd/Midrex Corp
LB	McMaster University
Nippon Steel	Nippon Steel Corp
Plasmadust	SKF Steel Co
Plasmasmelt	SKF Steel Co
Sumitomo SC	Sumitomo Metal Industries
XR	Kawasaki Steel Corp
AISI Direct Steelmaking	American Iron and Steel Institute (AISI)
IMIS	Institute Mexicano de Investigaciones Siderurgicas (IMIS)

* NKK's process was selected by the Japan Iron and Steel Federation for the Japanese national initiative - Direct Iron Ore Smelting (DIOS) project.

The AISI and IMIS processes are special cases in that their end product is slated to be not iron, as in the other 20 processes, but steel.

Table II shows the status of the processes named in Table I.

Table II: Status of Smelting-Reduction Processes

Process	Status
CIG	Paper study, abandoned
CBF	Essentially on hold during BSC's oxy-coal blast furnace tests; to be modified to the CCF process
COIN	Extensive pilot plant studies; no plans for demonstration plant
Combismelt	Potentially commercial; not being marketed
COREX	Commercial; 300 000 t/y plant, Pretoria Works, ISCOR
DIOS (NKK)	Demonstration plant, 500 000 t/y under construction at Keihin Works, NKK
Davy McKee	Pilot plant studies
Elkem Polar	Process development likely abandoned with scheduled closing of plant at Mo i Rana, end 1989
Elred	Essentially abandoned
Foster Wheeler-Tetronix	Abandoned or limited application; no news for some years
HIsmelt	Demonstration plant, 100 000 t/y, announced for Western Australia
Inred	Essentially abandoned; patent rights returned to inventor
KHD	Limited pilot-scale studies; no announced plans for further work
Kobe	Small pilot plant studies; now concentrating on DIOS project
LB	Laboratory scale; pilot plant plans
Nippon Steel	Small-scale pilot studies; now concentrating on DIOS project
Plasmadust	Limited application; single plant in south of Sweden treats alloyed steelworks (EAF) dust from across (Western) Europe
Plasmasmelt	Limited application; single plant in south of Sweden processes chromium ore
Sumitomo SC	Pilot plant studies; plans for demonstration plant abandoned: now concentrating on DIOS project
XR	Pilot plant studies continue even as Kawasaki participates in the DIOS project
AISI Direct Steelmaking	120 t/d pilot plant
IMIS	Pilot plant based on 6-tonne converter

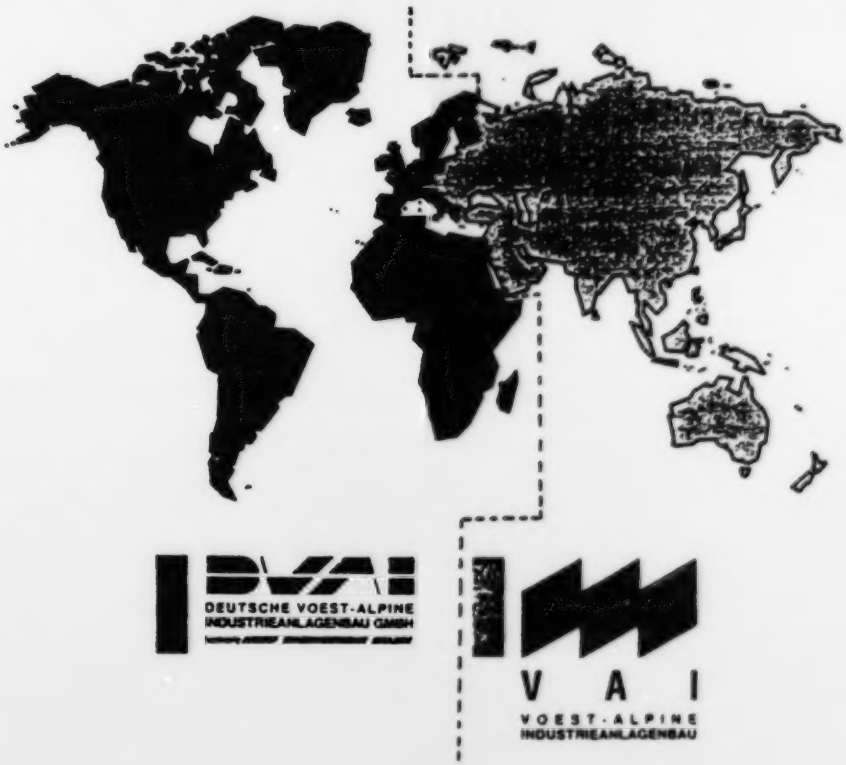
Of the ironmaking processes, the front-runners are COREX, HIsmelt, and DIOS. Each of these processes will be discussed individually. The AISI Direct Steelmaking process will also be discussed.

The objective of each of these developments is the production of liquid pig iron (steel in the AISI process) with lower capital costs than those of the traditional coke ovens/blast furnace route in a process that is environmentally friendly or can be made to be so.

COREX PROCESS

The COREX process, the first smelting-reduction process to be commercialized, is a joint development between Korf Engineering, FRG, and Voest-Alpine, Austria, with financial support from the Austrian Research Foundation and the Ministry for Research and Technology, FRG. The technology is now owned and marketed by Deutsche Voest-Alpine Industrieanlagenbau (DVAI), the successor to Korf Engineering, and Voest-Alpine Industrieanlagenbau (VAI). Their respective marketing spheres are shown in Figure 1.

Figure 1: Marketing Spheres - DVAI and VAI[1]



COREX technology is being promoted by DVAI as filling two gaps for the steel industry. First, it allows the large integrated steel producers to have a cost-effective unit for "swing" production of up to 600 000 thm/yr to supplement their large blast furnaces. Second, it provides the minimills with the possibility of producing hot metal at low cost even in small quantities, which is virtually a precondition for the minimills to enter the flat-rolled product market successfully.

Process Development

The COREX process was developed in response to a need, perceived in the late 1970s, to supply the minimill steel industry with a new source of virgin iron units. This role was being filled to that point largely by direct reduced iron (DRI), but natural gas prices rose so high at that time as to make additional gas reduction capacity unlikely in the markets envisioned. Process development proceeded as follows:

- 1977 - tests conducted in a modified casting ladle and, later on, in a small gasifier at Badishe Stahlwerke AG in Kehl, FRG,
- 1979 to 1980 - conceptual and pilot plant construction phase,
- 1981 - start-up of 60 000 tonnes/yr pilot plant at Kehl/Rhein, West Germany,
- 1981 to 1983 - process development,
- 1983 on - testing of the process with various ores (lump, pellets, sinter), and various grades of coal (from high volatile/high ash to anthracite) in a number of campaigns totaling more than 8000 hours,
- 1985 - ISCOR ordered the first commercial COREX plant, with a capacity of 300 000 tonnes of liquid iron a year for its plant at Pretoria,
- 1987, December - initial commissioning of ISCOR plant (shut down after one week),
- 1988, August 19 - start-up of ISCOR's COREX plant. First operating campaign ended in February 1989,
- 1989, February-November - debugging of plant,
- 1989, November 10 - plant restarted; capacity operation reached within four weeks,
- 1989, December 23 - COREX operation taken over completely by ISCOR and integrated into the production line of Pretoria Works,
- 1990, June 22 - official commissioning of COREX plant at Pretoria Works with Prime Minister de Klerk attending.

The pilot plant at Kehl/Rhein has been dismantled.

Subsequent to the successful August 1988 start-up, the ISCOR plant took a shutdown of several months for repairs and modifications - not entirely unexpected in a plant which is the first of its kind. The plant started up again at the end of October 1989 (on CVRD pellets) and within four days it had reached its design capacity of 40 tonnes/hour. When we visited DVAI on November 23, 1989, we learned that the ISCOR plant was operating at slightly less than capacity because one muffler on a compressor was cracked.

The DVAI people we met were pleased with the progress being made at the South African plant:

- hot metal analysis was on specification,
- sulfur was ranging between 0.01 and 0.04 percent,
- carbon content was 4.0 percent plus,
- silicon content was less than 1.0 percent.

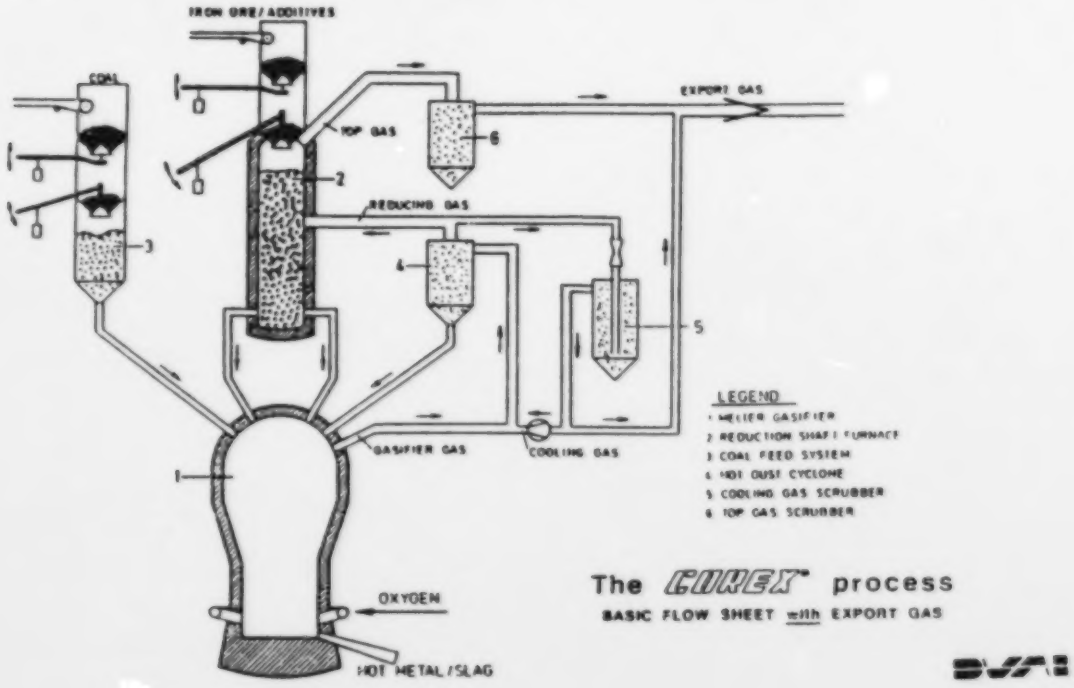
- slag CaO/SiO_2 was 1.15,
- hot metal temperature was 1500° to 1550°C, and
- FeO content of the slag was 0.5 percent.

The process has been operating on a steam coal mixture of 60 percent Delmas coal and 40 percent Wolvekrans coal; 13 to 15 percent ash, 20 percent volatile matter, about 0.6 to 0.7 percent sulfur. The coal rate was about 900 kg/thm but it was recognized that, with the high hot metal temperature being experienced, the coal consumption could be lowered. DVAI people believe they need one year of steady operation of the demonstration plant at ISCOR to fully prove the process.[2]

Process Description

In the COREX process the reduction of the iron ore is carried out in one vessel while the melting and residual smelting are carried out in another vessel. This separation is stated to impart a high degree of flexibility to the process permitting the use of a wide variety of untreated coals. A schematic arrangement of the process is given in Figure 2.

Figure 2: Schematic Arrangement of COREX Process[3]



The COREX process is designed to operate at pressures up to five bar. The coal and ore are charged through lock-hopper systems. The coal is stored in a pressurized feed bin and charged to the melter-gasifier by a speed-controlled feed screw. The coal falls by gravity into the melter-gasifier where it passes through a reducing gas atmosphere at a temperature of approximately 1000° to 1200°C where it is instantaneously dried and devolatilized, i.e. coked. All the higher hydrocarbons are cracked into CO and H_2, except for a small quantity of methane; therefore, no by-products (tar, benzols, ammonia, etc) are produced. Some decrepitation of the coal also occurs in this upper part of the

melter-gasifier. The reducing gas is produced in the fluidized bed of the melter-gasifier by partial oxidation of the coal with oxygen (98 percent purity) injected through radially disposed tuyeres; the carbon is oxidized initially to CO_2 which then reacts with free carbon to form CO. The gas temperature in the fluidized bed is 1600° to 1700°C. The gas leaving the fluidized bed contains 65 to 70 percent CO, 20 to 25 percent H_2 and 2 to 4 percent CO_2; the remaining constituents are methane, nitrogen, and steam. Upon leaving the melter-gasifier, the hot gases are mixed with cooling gas of the same composition to attain a temperature of approximately 850° to 900°C. This gas is cleaned in hot cyclones and then the bulk of it enters the shaft reduction furnace as the reducing gas. A small portion of the cleaned gas is diverted to the gas cooler to become cooling gas.

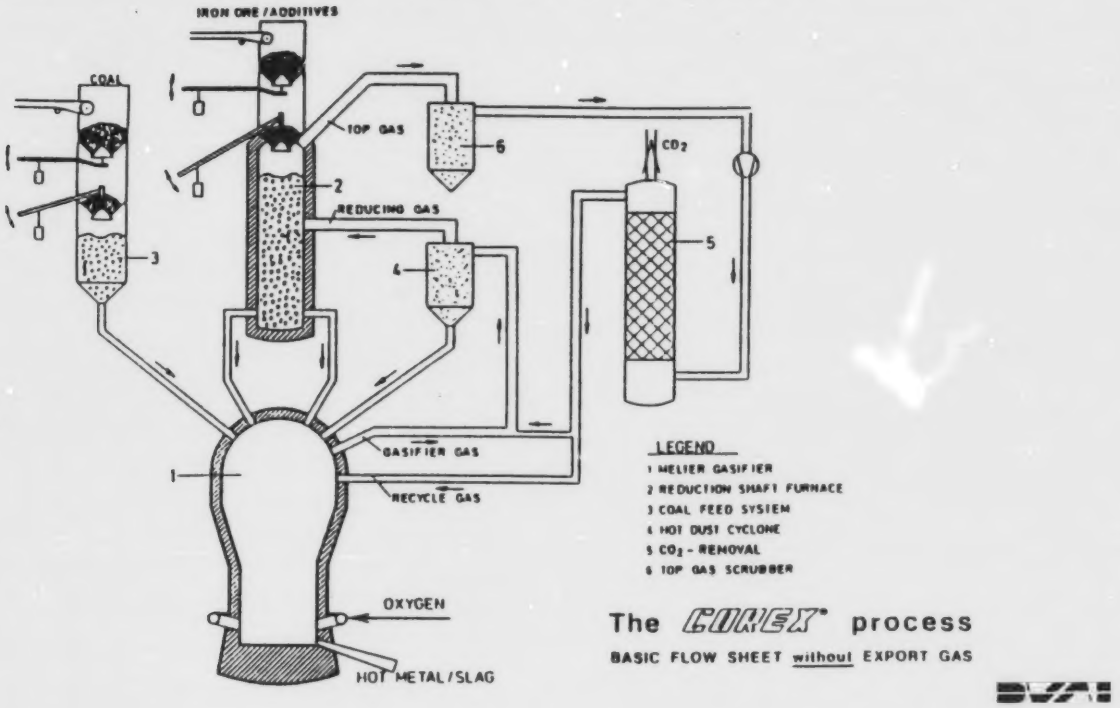
The fines captured by the hot cyclone are recirculated to the melter-gasifier. The reducing gas ascends through the shaft reduction furnace counter-current to the descending iron ore, heating the ore and reducing it prior to exiting at the top of the furnace. The top gas is cleaned and cooled in a scrubber, and is then available for export as a fuel gas (dust loading <10 mg/Nm^3; H_2S content <80 ppm). When using a high volatile bituminous coal, the export gas amounts to approximately 1800 Nm^3/thm having a net calorific value of about 8000 kJ/Nm^3.

The iron ore descends by gravity. According to DVAI people it attains metallization averaging 95 percent and contains three to six percent carbon, depending upon the raw material used and the operating conditions. The hot direct reduced iron (DRI), 800° to 900°C, is charged continuously to the melter-gasifier by a controllable transport system which discharges by hot screws into connected downcomers. The velocity of fall of the reduced iron particles is decreased in the fluidized bed, so that reduction is completed and the particles are heated and melted. Hot metal and slag drop to the bottom of the melter-gasifier and are tapped every 2.5 to 3.0 hours, on average, using procedures similar to those used in blast furnaces. The quantity of hot metal tapped was about 20 tonnes a tap from the pilot plant and has been 100 to 120 tonnes a tap from the commercial plant at ISCOR. For good desulfurization, DVAI aims for a slag basicity of greater than 1.0, i.e. $(CaO + MgO)/(SiO_2 + Al_2O_3) > 1.0$. The slag composition appears to be similar to that of blast furnace slag; the slag volume depends on the gangue content of the ore and the ash content of the coal.

The hot metal tapping temperature can be controlled in the range 1400° to 1600°C, according to DVAI. Gasification and DRI throughput are controlled so as to maintain the energy balance in the fluidized bed in equilibrium. The CO_2 content of the reducing gas exiting the melter-gasifier is the overall controlling parameter; it should be between 2.0 and 3.0 percent, and can be adjusted by a variety of process conditions. This CO_2 content primarily influences the carbon content of the DRI and its degree of metallization. The proper DRI carbon content leads to high carbon levels in the hot metal and low FeO levels in the slag - a necessity for good sulfur partition between the slag and the metal.

Figure 2 essentially describes the COREX process as practiced at ISCOR. A variation of the process, which can be used when the export gas is not desired, is shown in Figure 3.

Figure 3: Schematic Arrangement of COREX Process, without Export Gas[3]



In this case, the CO_2 in the gas exiting the direct reduction shaft is removed and the gas is circulated back into the melter-gasifier, which decreases the coal input to the process. The actual effect of this change may be seen by comparing the two flowsheets presented in Figures 4 and 5, both based on the design for a 40 thm/hr plant.

Figure 4: Flowsheet of COREX Process with Export Gas[3]

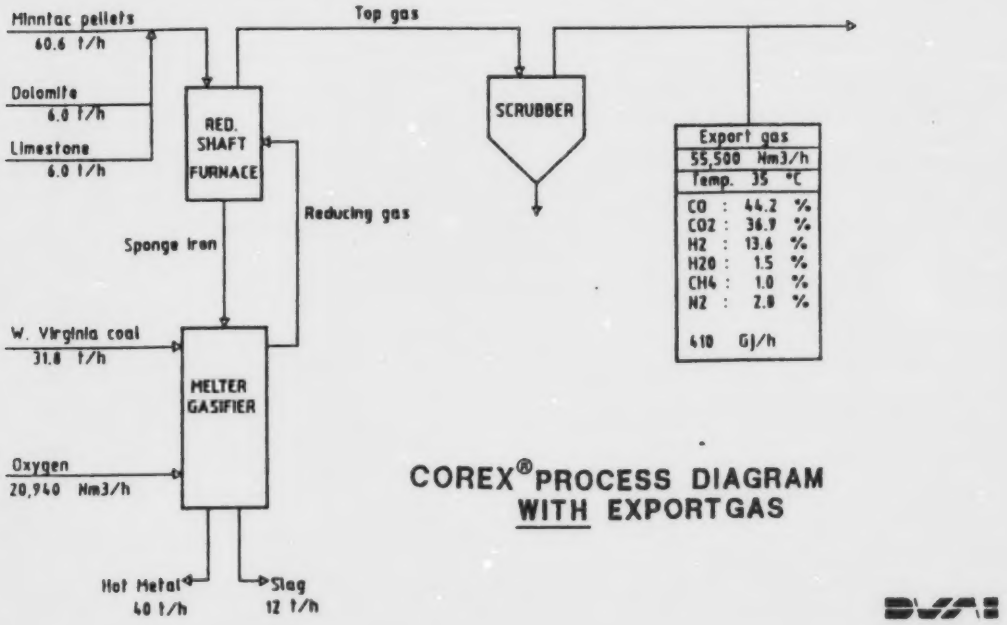
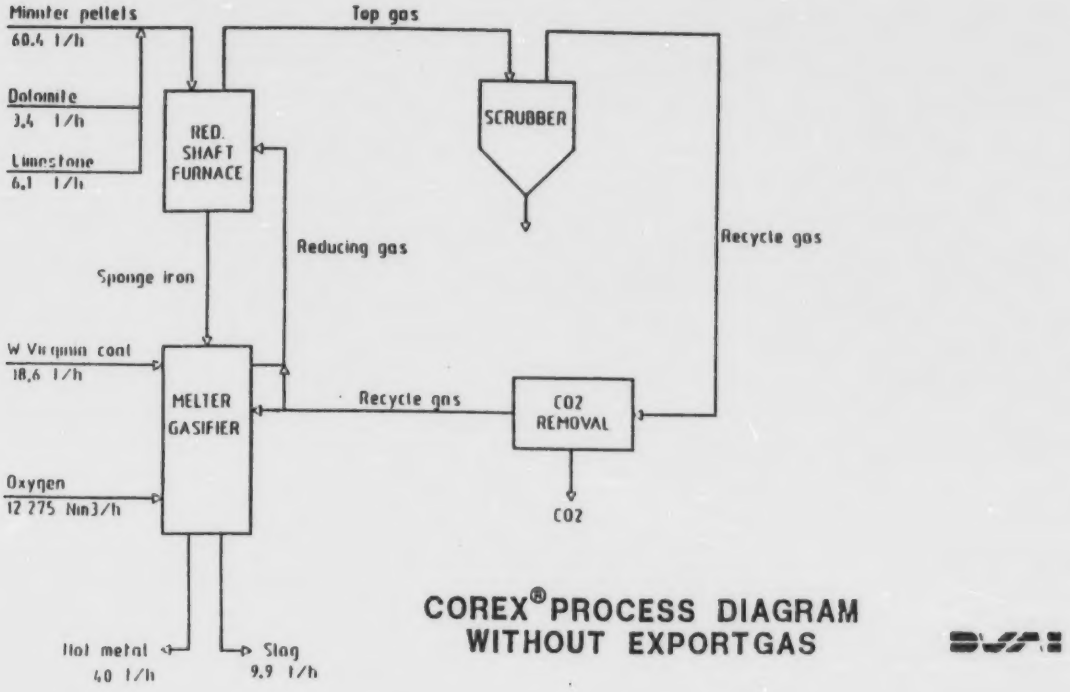


Figure 5: Flowsheet of COREX Process without Export Gas[3]



Raw Materials

Iron Ore

DVAI has tested a wide variety of lump ores, pellets, and sinter[3] in the COREX process, mostly in the 9.5 mm to 16 mm size range. They stated that they could process any type of ore in the COREX process provided the permeability of the burden in the shaft is good. What they prefer, on the physical side, are the following characteristics:

- uniform size,
- high reducibility, and
- "adequate" strength under reducing conditions.

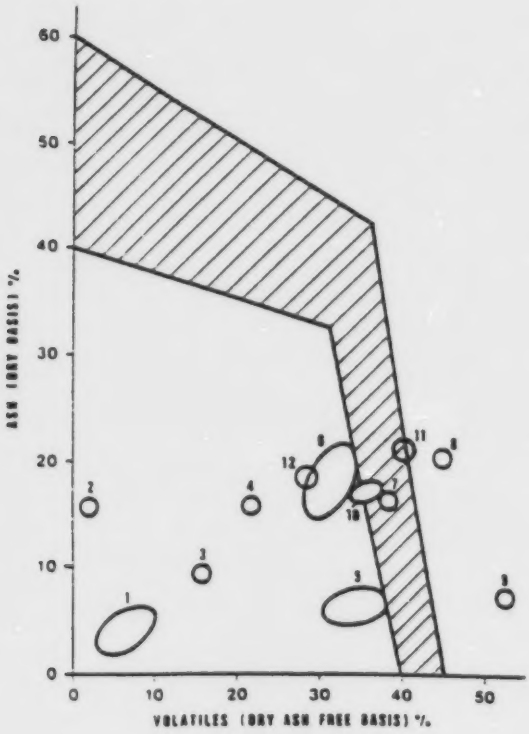
On the chemical composition side, the lower the gangue content the better, consistent with the physical requirements, since the higher the gangue content the higher the slag volume - which represents a cost to the process.

The Pretoria Works plant has been operating with an ore burden of 100 percent Thaba Zimbi ore, a South African ore which is also used on ISCOR's blast furnaces, screened to 6 to 12 mm. For some shorter periods, Sishen ore and CVRD (Brazil) pellets were also used.

Coal

DVAI has utilized a wide variety of coals[3,4] in the COREX process from anthracite to lignite, from high ash to low ash. In general, coal selection is based on availability and price. Figure 6 shows coal compatibility criteria.

Figure 6: Coal for the COREX Process[5]



1. anthracite
2. lignite char
3. West Virginia coal
4. Australian coal
5. high volatile bituminous
6. South African coal
7. high ash US coal
8. Indian coal
9. lignite
10. Brazilian coal CMSC
11. Brazilian coal CERS-1
12. Indian coal 2/3 + coke breeze 1/3

In Figure 6, those coals which are located to the left of, and below, the hatching can be used virtually without restriction in the COREX process.[3,4] Those to the right of the hatching, e.g. lignite, must be mixed with other coals of higher quality or be pretreated in some way. Those coals within the hatching, can be used, theoretically, but their usability must be confirmed by testing. DVAI looks for the following characteristics:

- volatile matter - This is the most important property, since it determines the gasification temperature. Coals with low volatile matter content generate a high temperature when gasified with oxygen, releasing sufficient thermal energy to melt the DRI. Coals with a high volatile matter content, such as lignite, generate a much lower temperature because of the high thermal requirements to crack their volatile hydrocarbons. Such coals must be mixed with anthracite, low volatile bituminous coal, coke breeze, or charcoal.

- ash content - Low ash content is preferred, but this property is less critical, since compensation for the mainly acidic ash can be made by flux additives to form slag of the required composition.

- particle size - Unprepared coal should have a size distribution of 0 to 50 mm. Its fines content, i.e. less than 1.0 mm, should be no more than 10 percent and its coarse content, i.e. greater than 35 mm, should be no more than 20 percent.

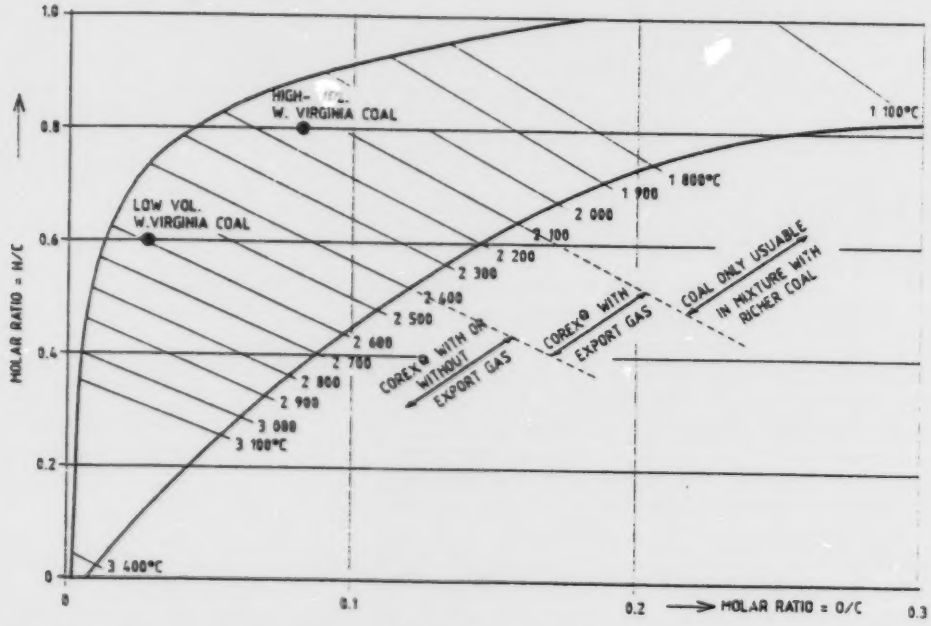
- moisture content - Up to 8.0 percent, the coal need not be dried; coals with a higher moisture content must be predried in a state-of-the-art coal drying facility.

Other properties, such as ash melting behavior, swelling index, and Hardgrove index are of little or no concern.

Petroleum coke is well suited to the COREX process because of its high carbon content. Its low reactivity has no adverse effect. If necessary, those with the higher sulfur contents can be blended with low sulfur coals to reduce the sulfur input per tonne of hot metal.

Figure 7 gives more information on the different process possibilities when a coal quality is given.[5]

Figure 7: Meunier Diagram of the Adiabatic Gasification Temperatures[5]



The Meunier diagram characterizes the coal grades by H/C and O/C molar ratios and shows the different adiabatic gasification temperatures.

According to Figure 7, knowing the chemical composition of a coal (including ultimate analysis) allows the selection of the right process flowsheet and the prediction of the amount of export energy. Such information can also be based on coal mixtures.

Fluxes

Limestone and dolomite are added, based on the gangue content and analysis of the ore and the ash content and analysis of the coal, to adjust the slag basicity. Silica sand is added in the situation in which the Al_2O_3 content of the slag would be too high and needs to be diluted. The fluxes are charged either with the coal or with the ore via the reduction shaft in which case they arrive at the melter-gasifier precalcined.

Economic Considerations

Based on a rated capacity of 300 000 t/y, the same capacity as the ISCOR plant, the capital cost of a COREX plant is DM450 (US $250 at 1.8 DM/US $) an annual tonne of hot metal. This plant does not recycle the gas but, rather, exports it all for fuel. The cost of hot metal from such a plant is shown in Figure 8 as a function of ore and coal costs.

Figure 8: Hot Metal Cost with COREX (without Gas Recycling)[1]

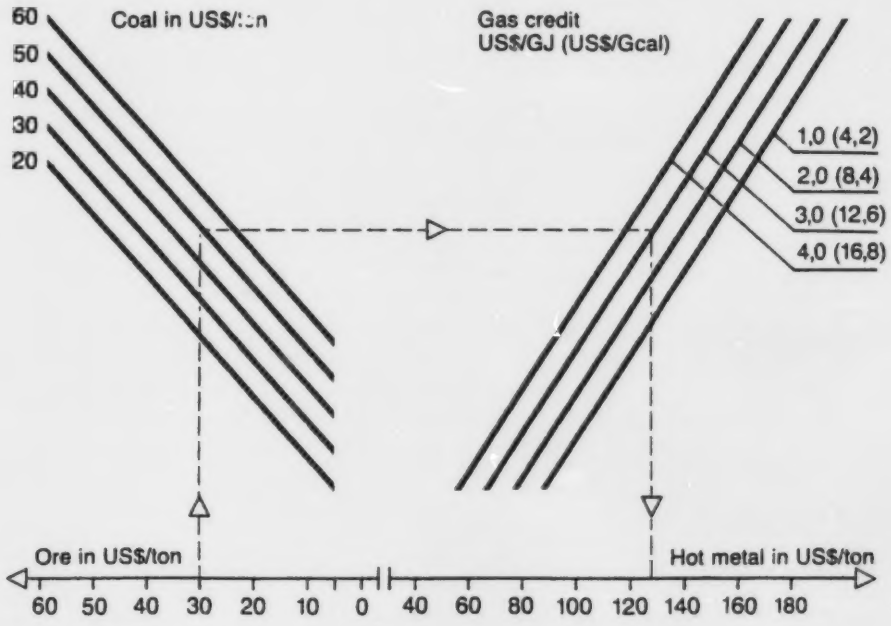


Figure 8 includes the following:

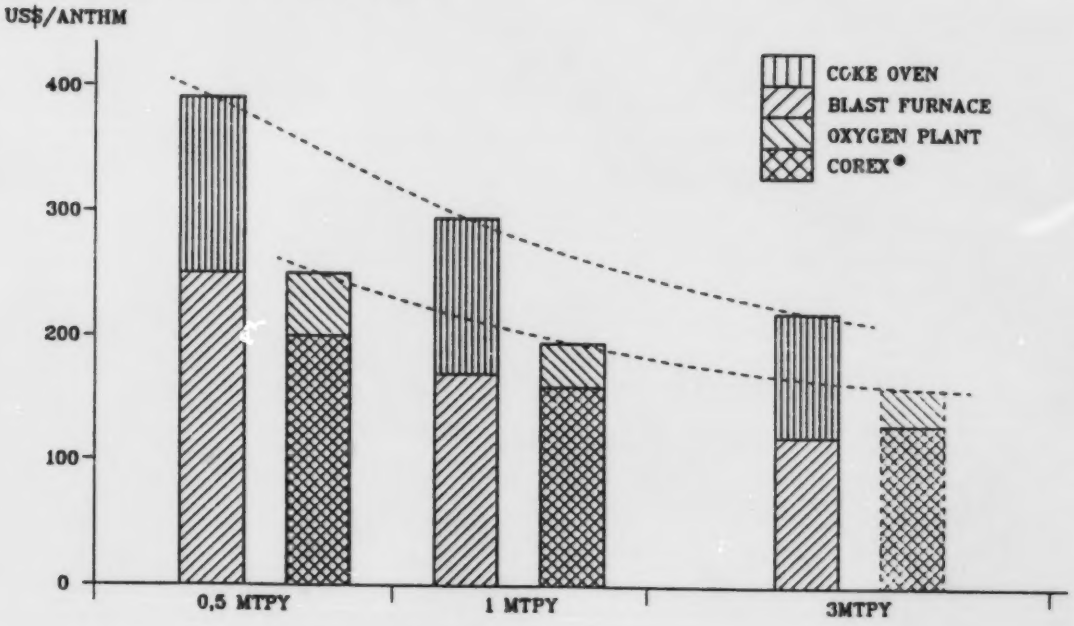
- cost of capital ..... 10 percent, 15 years
- cost of oxygen ..... US $0.04/$Nm^3$
- cost of electric power ..... US $0.04/kWh
- labor cost (50 people) ..... US $20 000/y.person
- maintenance cost ..... 4.0 percent of equipment cost

With gas recycling, the investment cost is about 10 percent higher than without. However, this higher investment cost, due essentially to the CO_2 removal equipment, is in large measure compensated for by lower operating cost because less coal and oxygen are required. The lower oxygen requirement also lowers the investment cost for the oxygen plant.

Integrated Steel Plants

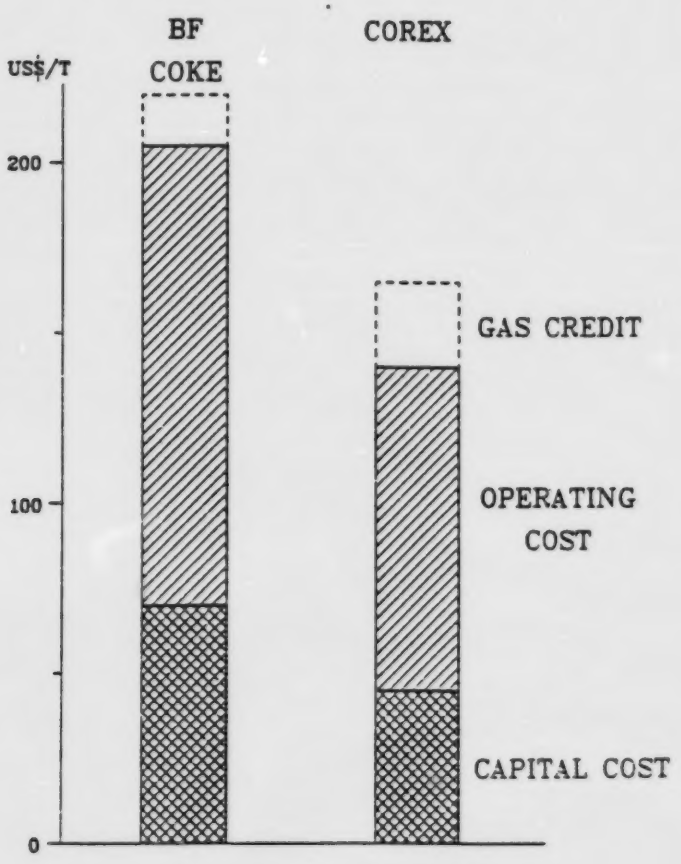
The chemical composition and temperature of the hot metal from the COREX process is well suited for BOF steelmaking. COREX can be built in units producing 300 000 to 600 000 t/y. It can either replace smaller blast furnaces in existing integrated steel plants or serve as a swing producer of hot metal to complement the output of large blast furnaces. Compared to the conventional coke oven/blast furnace route, COREX has a much lower investment cost - mainly by the elimination of the coke oven plant. Figure 9, developed by DVAI, indicates that capital costs for the COREX process range from US $160 to US $250 an annual tonne of iron, compared to US $220 to US $390 for the coke oven/blast furnace route.

Figure 9: Capital Cost Considerations[6]



The lower investment cost also influences the cost of the hot metal produced. A comparison developed by DVAI is shown in Figure 10.

Figure 10: Hot Metal Costs[6]



These cost figures are based on a coke oven/blast furnace complex having a capacity of one million tonnes a year versus two COREX modules each with a capacity of 500 000 t/y. In this comparison, COREX has an unfair advantage in that the COREX units are almost maximum size while the blast furnace is a small furnace, which must be kept in mind when considering the cost numbers. The calculations indicated that COREX hot metal would be less costly than blast furnace hot metal by about 32 percent. (Actual operating experience at ISCOR has indicated that the COREX process is producing hot metal 25 percent more cheaply than conventional ironmaking - according to ISCOR officials.[7]) The savings are due mainly to the lower net energy cost, the lower labor cost, and the lower investment cost of the COREX process. Assuming that the cost for further processing of the hot metal to steel would be the same in both cases, the net saving with the COREX process has been estimated by DVAI to be over US $66/tonne of steel.

DVAI states in its literature that alkalis in the ore, which would cause severe problems in a blast furnace, both to the operation and to the refractories, can be handled with no real difficulty in the COREX process. They hold this out as an added "plus" for the COREX process in that it broadens the range of ores that this process can smelt. However, some opinions were expressed to us on our visits (not by DVAI people) that the problems that the COREX process was encountering upon switching from CVRD pellets to Sishen ore could very well be caused by the high alkali content of the Sishen ore.

Minimill Steel Plants

The success of the minimill steel plants was based on the low-cost production of long products such as reinforcing bar, wire rod, and smaller sections. These were products which did not need high quality steel and could be produced economically with small capacities and moderate investment. Now, many of these mills are trying, some quite successfully, to extend their production to more sophisticated products like forging bars, cold heading steels, and flat-rolled coils and sheet.

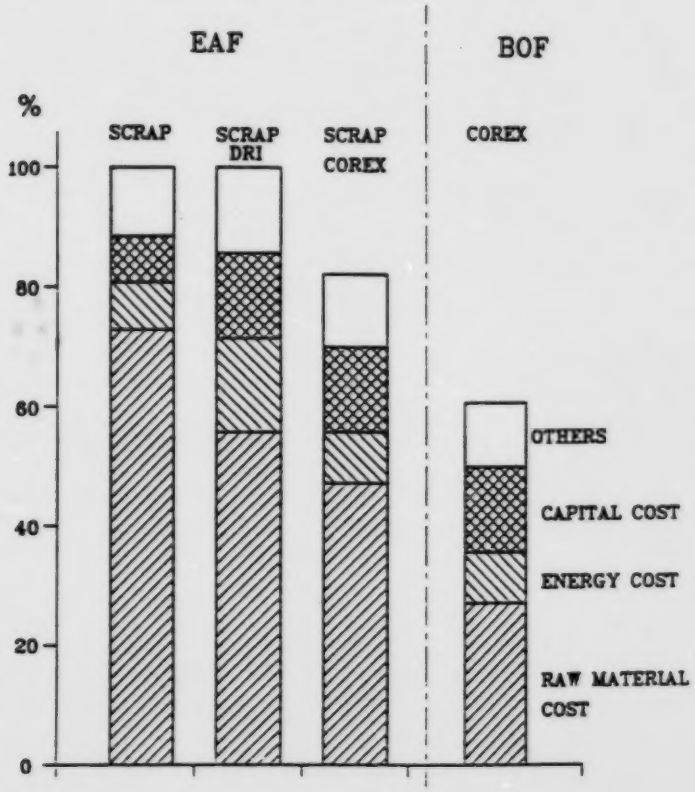
One of the major problems encountered in extending into the higher quality products, and a problem which the integrated steel plants do not have to face, is the problem of residual elements in the steel - the result of 100 percent reliance on steel scrap as the raw material. This problem is minimal for those plants which are able to practice the selective charging of scrap containing low or desired residuals. Such selectivity, however, may be possible only when scrap is in good supply. Some plants resolve the problem by diluting the residuals through the charging of virgin iron units in the form of direct reduced iron (DRI), hot briquetted iron (HBI), cold pig iron, or even hot metal.

In the past, when hot metal has been charged to the electric arc furnace, a bucket of scrap would first be charged and then hot metal, to the extent of 30 to 50 percent of the charge, would be added by means of a refractory-lined launder. The power was on during the charging of the hot metal and oxygen was blown simultaneously. This same practice is suggested for the COREX process; the COREX process is stated to be able to produce hot metal very economically in the smaller units that would be needed by the minimills.

Another possibility for producing flat products would be the processing of the hot metal from a COREX plant in a BOF. A 500 000 t/y COREX plant, in combination with a 60-tonne BOF vessel, or a modification thereof, would provide steelmaking capacity of 550 000 to 650 000 t/y.

DVAI's cost calculations to produce 800 000 t/y of steel by electric arc furnace and by BOF steelmaking, using hot metal produced by the COREX process, are shown in Figure 11.

Figure 11: Steelmaking Costs - EAF and BOF[6]



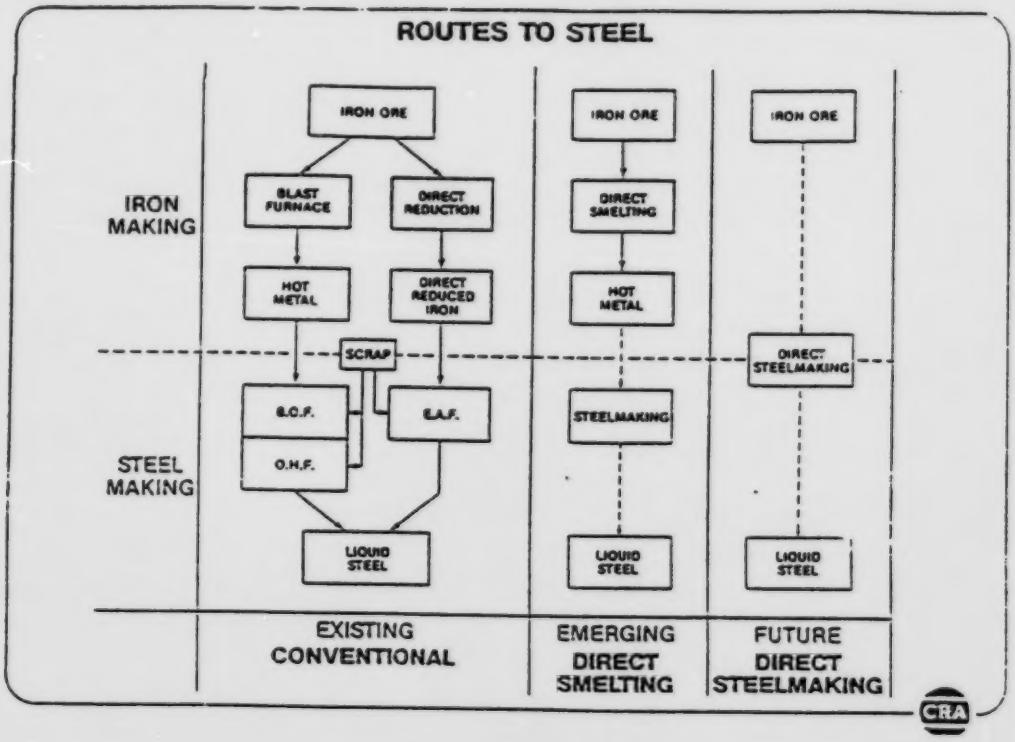
DVAI's figures indicate that, at present raw material costs, for EAF steel produced from 100 percent scrap, or from 50 percent scrap and 50 percent DRI, the steelmaking cost is just about the same; the increased cost for energy and capital associated with the use of DRI approximates the cost of the scrap it replaces. Significant cost savings are indicated by substituting hot metal by the COREX process for scrap. In this case, both raw material and energy costs will be decreased because coal is less expensive than natural gas and the demand for electrical energy will be reduced by approximately 50 percent. Even lower costs are indicated for processing the output from the COREX plant in a BOF.

HIsmelt PROCESS

CRA (formerly Consolidated Rio Tinto Australia) first became involved in investigating available ironmaking technologies in response to the obligations which form part of the agreements between Hamersley Iron, a 100 percent subsidiary of CRA, and the State of Western Australia. Studies directed towards establishing plants in Western Australia for the further processing of iron ore to "value added" products have been undertaken since the start of Hamersley shipments in the mid 1960s.

The three main process routes to steel, using intermediate iron production, are shown in Figure 12.

Figure 12: Process Routes to Steel[8]



CRA decided to investigate smelting-reduction - the production of molten iron from iron ore and steam coal with the minimum of pretreatment of the key materials. Early in 1981 they established the criteria which they consider to be essential for the successful development of a coal-based smelting-reduction technology:

- use of natural iron ore fines,
- use of a wide range of coals,
- ability to minimize surplus off-gas,
- use of post-combustion, and
- simple design - to minimize capital costs.

Process Development

CRA needed to develop a process; Klöckner Stahlforschung had the technological expertise, and the experience, of injecting solids into liquid steel (from their KMS and KS processes). These two companies reached an agreement to jointly develop an iron bath smelting-reduction process. Process development proceeded as follows:

- 1981 - agreement reached between CRA and Klöckner Stahlforschung, followed by the establishing of a joint venture to undertake the major process development.
- 1982 - testing of the principles of the process in an existing 60-tonne KMS converter proved its technological feasibility.
- 1982 to 1984 - planning and erecting a pilot plant, to thoroughly develop the process, at the Maxhütte Works of Klöckner-Werke, Sulzbach Rosenberg, Bavaria, FRG.
- 1984 - start-up of pilot converter having an annual capacity, in continuous operation, of 30 000 tonnes of hot metal.
- 1984 to 1990 - development of the process continued at the pilot plant, despite the fact that Klöckner relinquished their interest in this process to CRA during this time period.
- 1987 - CRA's and Klöckner's interests were restructured and CRA obtained sole rights to the technology under development.
- 1989 - Midrex Corporation, now a subsidiary of Kobe Steel Company, Japan, obtained 50 percent ownership of the process which is now known as the HIsmelt (High Intensity smelting) process. Midrex people joined the research team in Germany.
- 1990, June 13 - pilot plant work completed at Maxhütte Works.[9]

The HIsmelt development program has achieved the objective of utilizing natural ore fines. It has also demonstrated that a wide range of noncoking coals can be used in the process. Medium rank coals can be used directly, while some lower rank coals would require a preliminary drying stage - possibly utilizing the waste heat contained in the process tail gas.

The pilot plant at Sulzbach Rosenberg has operated over a wide range of conditions, achieving high levels of post-combustion and high heat transfer efficiencies. The resulting coal consumption rates compare well with those of the blast furnace. Furthermore, preheated air has been used successfully in place of oxygen.

In addition to the extensive pilot plant investigations in Germany, CRA undertook a major support program in several areas, including:

- mathematical modeling,
- fundamental studies by CSIRO, Melbourne, Australia,
- flow sheet studies, and
- engineering studies.

The next stage in HIsmelt process development is the construction and operation of a demonstration plant in Australia and planning is under way as follows:

- the project will be undertaken by HIsmelt Corporation Pty Limited, a new (1989) joint venture between CRA Limited and Midrex Corporation, USA.

- the major engineering will be done by Davy McKee, Stockton, UK. At the conclusion of the development work there will be two engineering licensees, Midrex and Davy McKee.
- the facilities and the research program are expected to cost A $100 million.
- the facility will be sized to produce 100 000 tonnes/yr of pig iron.
- this major research facility is slated to be built at the Kwinana blast furnace site of BHP (shut down by BHP in 1982) because of the existing infrastructure.
- the plans were in the public (environmental) review period when we met the HIsmelt representative in November 1989.

The construction and operation of the demonstration plant is required to:

- confirm scaleup parameters,
- determine accurate operating costs,
- demonstrate continuous operation,
- confirm capital costs, and
- establish commercial plant configuration.

CRA would like to start construction of the demonstration plant by mid 1990 and to have their work completed by 1995 but construction could be delayed to as late as mid 1991.[9] Ultimately, the demonstration plant will be used to test the coals, ores, and even the ideas of seriously interested potential clients.

Process Description

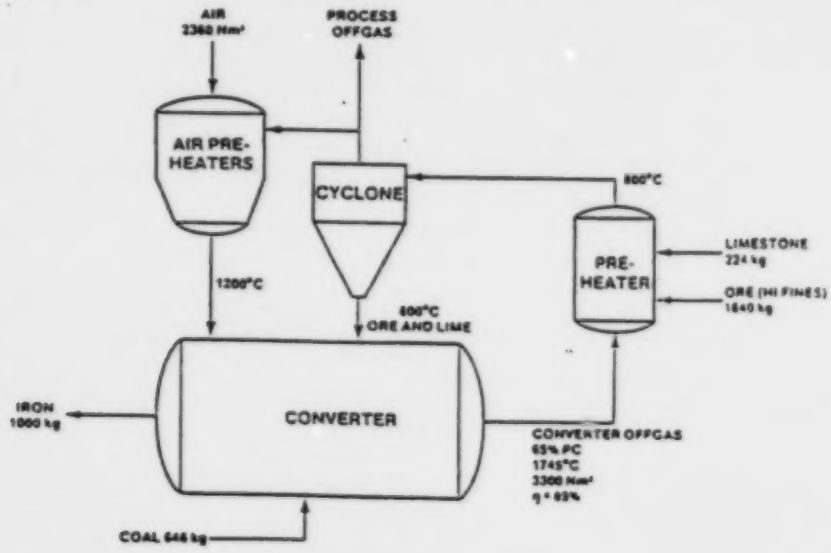
The heart of the HIsmelt process is a horizontal cylindrical reactor, the only equipment used in this process that is not a standard off-the-shelf item. It is lined with standard steelplant refractories. At this stage of development, no water-cooling is used in the construction members of this vessel; presumably it will in the demonstration plant.

This reactor has a relatively shallow bath with a maximum of surface area, which allows higher post-combustion rates and greater heat transfer.

The HIsmelt process is based on the injection of coal, iron ore, fluxes, and various gases into a molten iron bath. In a highly stirred state, the molten bath acts as a very intensive reaction medium, permitting rapid heat transfer rates at high efficiency and at high mass transfer rates. Many complex reactions and interactions take place simultaneously in the iron bath vessel. A key factor to the viability of this process is the efficient injection of solid materials into the iron bath.

Air, not pure oxygen, is used in the HIsmelt process. The large volume of hot gases exiting the reactor vessel can be utilized to preheat the incoming air to achieve economies in energy consumption; the cost of generating pure oxygen is avoided, but there is increased cost for cleaning the much larger volumes of waste gas. (While CRA personnel don't talk about it, oxygen-enriched air could be a good compromise.) They intend to recirculate the dust from the gas cleaning operation back to the molten bath, possibly via bottom injection. The flow sheet is shown in Figure 13.

Figure 13: Flowsheet of HIsmelt Process[8]



The crucial element in the HIsmelt concept is the efficient and effective transfer of the energy contained in the generated gases back into the melt - by post-combustion of these gases within the smelting-reduction vessel, coupled with controlled stirring of the bath. The combustion conditions, and interaction with the bath surface, and bath stirring are established to maximize the formation of CO_2 and steam in the exit gases, as well as to maximize the energy transfer from the combustion reactions to the molten bath. Learning how to maximize energy release and effect its transfer at high efficiency levels back to the bath has been the key thrust of the development program and much effort has been expended in this direction.[10] Recent advances have produced stable operating conditions in the 50 to 60 percent post-combustion range. These advances encompass new equipment design and operating practices, incorporating both "evolutionary developments" and "radical alternatives"[10] [proprietary - no details provided].

HIsmelt has stated publicly that the process can use a range of coals. The coal is ground and injected the same as for the KMS process.

The HIsmelt process uses direct shipping ore fines containing about 62.5 percent iron; it has the standard Hamersley ore analysis, as shown in Table III (percent dry basis).[11]

Table III: Typical Chemical Analysis - Hamersley Ore[11]

Component	Percent by Weight	Component	Percent by Weight	Miscellaneous
Fe_T	62.4	MnO	0.090	Cu, 0.002
FeO	0.12	CaO	0.06	
SiO_2	4.10	MgO	0.05	Co, As, Sb, Pb, Sn, V, and Bi are all at 0.001 percent.
Al_2O_3	2.50	Na_2O	0.011	
P	0.075	K_2O	0.008	Moisture is typically 4.7 percent
TiO_2	0.13	Cr	0.004	
S	0.020	Ni	0.002	
LOI	3.50	Zn	0.002	

The size analysis on loading (natural basis)[11] is typically as shown in Table IV.

Table IV: Size Analysis[11]

Size (mm)		Percent by Weight
	+8	1.0
-8	+6	6.8
-6	+3	30.6
-3	+0.25	37.0
-0.25	+0.15	8.5
-0.15	(dry)	16.1

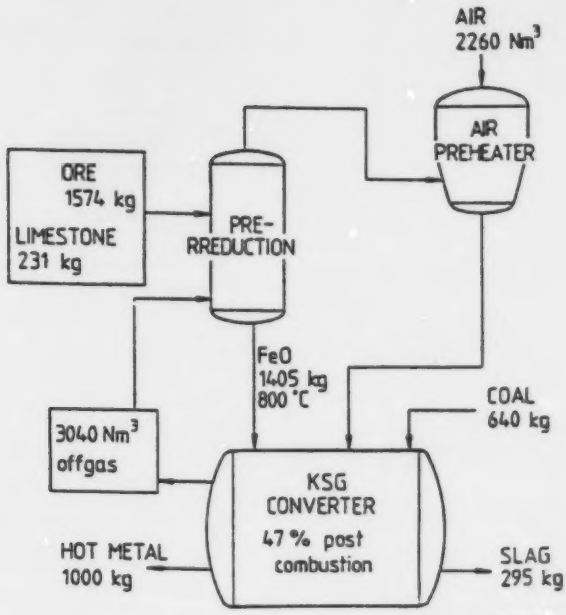
It is not HIsmelt's intention, at this time, to add scrap to the melt, although there are apparently some who would like them to.

The product of the HIsmelt process will be a direct feed to steelmaking operations. Its carbon content is controllable and deliberately variable; they can reach the same carbon levels as blast furnace iron if they choose to do so. They would like to desulfurize the hot metal externally. The slag composition depends on the charge materials, but it is expected to be similar to that of blast furnace slag, although the FeO content is stated to be similar to that in the OBM process. The iron produced from Hamersley ore contains about 0.075 percent phosphorous, but we were told that they can deal with this situation. We were not told how they propose to do so.

According to Dr. Philp, our contact at HIsmelt, the process is controlled by means of their mass balances; he would not elaborate.

In Klöckner's KSG process, the forerunner to the HIsmelt process, provision was made for the prereduction of the iron oxide of the ore to wustite (FeO) prior to injecting it hot into the molten bath. With this refinement, the HIsmelt process flowsheet becomes that shown in Figure 14.

Figure 14: Flowsheet of HIsmelt Process with Prereduction[12]



While HIsmelt has apparently concentrated on the injection of untreated ore fines, laboratory work has been carried out on the reduction of iron ore fines to wustite. Wide ranges of temperatures and gas compositions have been examined. By avoiding the formation of metallic iron, conditions have been found at which iron ore can be reduced in relatively short reaction times without sticking. The results pointed to the feasibility of incorporating a preheating/wustite reduction unit into the smelting process. One further consideration is the relationship between post-combustion and prereduction. The reduction of Fe_2O_3 to FeO becomes more difficult as the oxidizing potential in the off-gas is increased (through increasing post-combustion). In addition, due to relatively short residence times, the iron ore in a particular size range is not fully reduced to FeO. Thus, the concept of average prereduction is introduced. The average degree of prereduction determines what the coal consumption will be; it is not important, then, if some of the larger particles are not so fully reduced as the smaller ones. Calculations have shown[10] that for a given coal consumption of 650 kg/thm, a post-combustion level of about 45 percent requires prereduction to FeO. As the post-combustion level rises to around 65 percent, the required level of prereduction decreases to zero.

HIsmelt has no experience, yet, with a hot connect between the prereduction stage and the smelting-reduction stage. However, they have every confidence that this problem is solvable and, when it is needed, they will be able to engineer it for their process.

Further work regarding the incorporation of prereduction to wustite followed by hot charging into the reactor, including flowsheet development and experimental investigations, is anticipated.

Economic Considerations

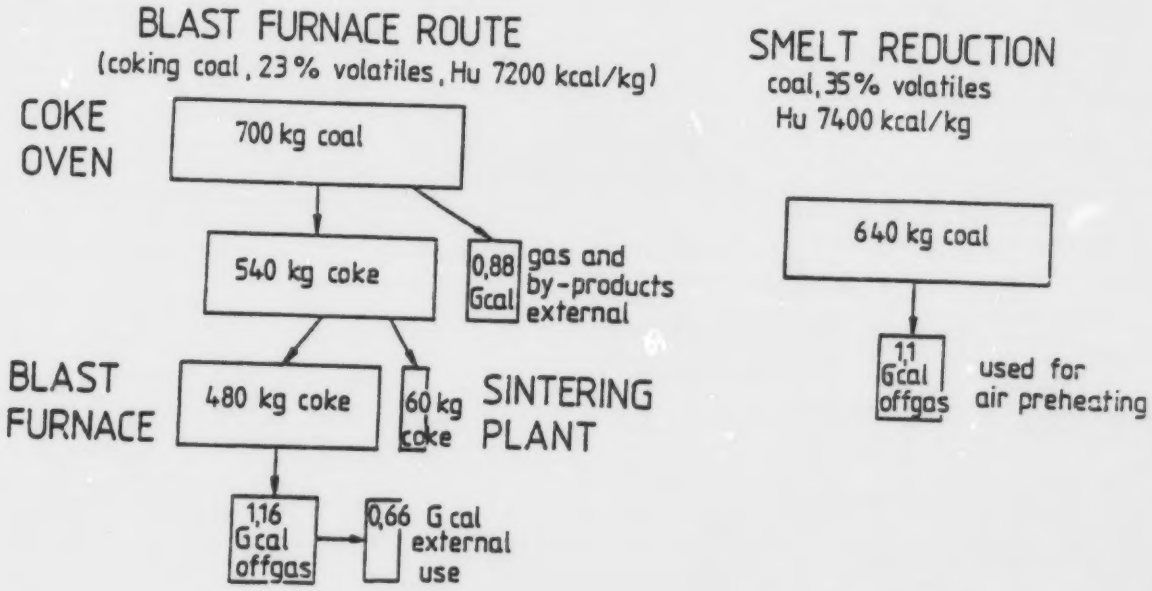
The HIsmelt Corporation has not published its estimates of capital costs to build a commercial HIsmelt plant, nor has it published its estimates of operating costs for such a plant. However, the statement was made to us that they want to be competitive with the blast furnace regarding capital

cost on a greenfield site. They expect their operating costs to be lower than those of a blast furnace, which they see as their major competitor. They view the HIsmelt process as one which could prove to be a viable replacement for blast furnaces in the Western world and, probably, also in China. It could have the role, as well, of supplementing blast furnace output.

Obviously, they are looking to their demonstration plant to provide the data upon which to calculate realistic estimates of capital and operating costs. They also expect to determine from it the optimum size of plant for this process. The first commercial unit is expected to be sized to produce 500 000 t/y, five times the capacity of the demonstration plant.

The HIsmelt process compares with the blast furnace on the basis of raw materials requirements as follows. To produce one tonne of hot metal by either process, assuming the same hot metal composition, would require the same weight of ore; the flux additives would also be essentially in the same quantities. The difference between these two routes to hot metal, if there is any, would be in the quantity of coal that would be required. Figure 15 is HIsmelt's simplified comparison of the two processes on the basis of their energy needs.

Figure 15: Energy Requirements Comparison[13]



note: Hu = heating value

In the coke oven/blast furnace route, the energy is utilized largely in a complex interconnected system. This route achieves a high level of energy efficiency. In fact, by HIsmelt's own example, it requires less net energy than does the HIsmelt process, as noted below:

- Coke ovens/blast furnace ..... energy in = 5.04 Gcal/thm
  recovery = 1.54 Gcal/thm
  ---
  net energy = 3.50 Gcal/thm

- HIsmelt ..... energy in = 4.74 Gcal/thm
  recovery = 1.10 Gcal/thm
  ---
  net energy = 3.64 Gcal/thm

The lower net energy requirement favors the coke oven/blast furnace route. However, some features do favor the HIsmelt process, including:

- the ability to use a wider range of coals and thereby take advantage of any lower coal prices, and

- the lower complexity of their system, which is operated so as to provide sufficient energy in the reactor off-gas to preheat the air to 1200°C, but to produce no surplus energy that has to be used in interconnected systems.

Licensing Arrangements

Licensing arrangements have not been finalized; they are still several years away from having a proven, operating process to sell. The most likely arrangement would be a lump sum payment based upon a fixed tariff per tonne of capacity. Just how the process will be marketed and to whom the license fee would be paid have yet to be clarified. These considerations and, indeed, their whole future marketing strategy are probably low on HIsmelt's priority list at this time.

The two engineering licensees will be Davy McKee and Midrex.

DIRECT IRON ORE SMELTING (DIOS) PROCESS

The Japanese development of a smelting-reduction process for producing molten iron was initiated, in April 1984, as a national project under the name DIOS (Direct Iron Ore Smelting) project. It is sponsored by the Japan Iron and Steel Federation and is the responsibility of the JISF's R&D Task Force/Committee for Research and Development of the New Iron Ore Smelting Process. The task force to develop the DIOS process comprises 12 research engineers and three general affairs managers. The DIOS process is aimed at blast furnace replacement leading ultimately to a 10 000 tonnes a day plant.

Funding by the Ministry of International Trade and Industry (MITI) is "relatively small" and is provided by the Coal Division through the Coal Mining Research Centre (CMRC). CMRC do not participate actively in this study; they only provide the avenue for government funding. Total research and development costs are expected to exceed US $87 million over the seven-year life of the project (budget ¥13 000 million).

The members of the consortium supporting the DIOS project include:

- Godo Steel, Limited,
- Kawasaki Steel Corporation,
- Kobe Steel, Limited,
- Nakayama Steel Works, Limited,
- Nippon Kokan KK,
- Nippon Steel Corporation,
- Nisshin Steel Company, Limited, and
- Sumitomo Metal Industries, Limited

These companies have been cooperating over the past three years to develop elementary technologies. The specific contributions of the various companies are the following:

Kawasaki Steel Company

KSC developed their own process, the XR process, which differs from the process development at NSC and NKK in that there is no post-combustion of the gas.

KSC are researching fluidized bed prereduction for the national project, even while, apparently, continuing their work on developing the XR process.

Kobe Steel Company

Kobe are developing the operating principles and design parameters of the gas reformer which will be part of the collection pipe leading from the smelting-reduction furnace to the prereduction furnace. The work is focused on increasing the reducing potential of the gas for prereduction and the export of a high quality heating gas (same role as solution loss reaction in the blast furnace, i.e. C [from coal] + CO_2 [in gas from smelting-reduction furnace] → 2CO), with improved energy utilization.

Nippon Kokan KK

Prior to entering into the joint program, several of the member companies had been working to develop their own respective process of smelting-reduction. The NKK process was selected to be the basis for the DIOS process.

NKK carried out their process development in a 5-tonne vessel. In their preferred version of the process, the smelting-reduction furnace should be pressurized to about two atmospheres, the advantages being smaller gas handling equipment, better post-combustion, and less slag foaming.

NKK developed a simulation model; it indicates that the process should aim at 15 to 20 percent prereduction and 60 percent post-combustion at 2.0 atmospheres.

NKK have indicated plans to do some basic research on post-combustion.

Nippon Steel Corporation

NSC has carried out extensive research on the bath smelting of iron, i.e. the reacting of coal, iron ore, and oxygen in a liquid bath to produce iron. They are now carrying out bath smelting trials on a 180-tonne BOF vessel at Sakai Works.

NSC has developed a mathematical model of the entire process, including prereduction via a single-stage fluidized bed at 800°C; their aim is to have the energy of the off-gas to be approximately 1.0 to 2.0 Gcal/thm, which is similar to that of blast furnace gas.

NSC is initiating work on the fundamentals of slag foaming; they intend to determine the effects of slag composition, bubble size, etc.

Sumitomo Metal Industries

SMI are completing experiments for the national project using the 10-tonne converter available at Kashima Works. They are examining how to increase heat transfer in the smelting furnace so as to lower the carbon rate. Their work includes the technique for oxygen mixing in the slag layer and, also, refractory selection.

Based on the findings and accumulated know-how from these efforts, a 500-tonnes/day pilot plant is scheduled to start operation in July 1993 at an idled steelmaking shop at NKK's Keihin Works. The plant will be operated for one to two years to finalize the process development. The overall schedule for the research and development of the DIOS process is given in Table V.

Table V: Research and Development Schedule - DIOS Project[14]

Fiscal Year	1988	1989	1990	1991	1992	1993	1994
I. Study on Components for DIOS-Process (1) Smelting Reduction Technology (2) Prereduction Fluidized Bed Technology (3) Gas Reforming Technology (4) Integration Technology							
II. Pilot Plant Study (Integrated Facility based on In-Bath Smelting Furnace with 500 t/D capacity)				Design & Construction		Operation	
III. Total System Study and Feasibility Study on DIOS-Process							F/S

The completion of the 500 t/day pilot plant study coincides with the time at which replacement of coke ovens has to be considered.[15]

Process Description

Figure 16 is a schematic diagram of the DIOS process being developed by the JISF.

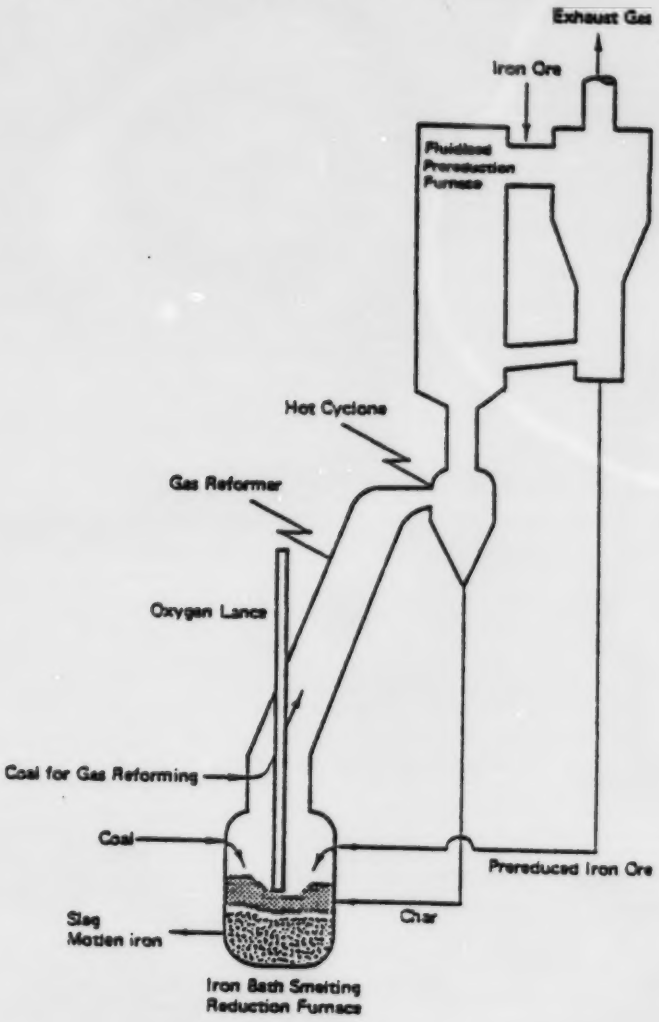
The DIOS process has three possible configurations:

- the smelting-reduction furnace only,
- the smelting-reduction furnace coupled to a prereduction furnace, and
- the coupled smelting-reduction furnace and prereduction furnace in combination with a coal-based gas reformer and/or a CO_2 removal system.

When the smelting-reduction furnace and the prereduction furnace are connected, the connecting pipework will be used as a coal-based gas reforming furnace; details of its design and functional capabilities were not provided. The pilot plant will be designed for in-bath smelting, the technology that NKK had been working to develop. The furnace for prereduction had not been designed at the time of our visit, but it, too, will be built at the pilot plant at Keihin Works.[16] In-bath smelting was selected for:

- high productivity,
- flexibility (wide range) in coal selection,
- high post-combustion, and
- the direct use of lump or coarse coal and ore. (For kinetic reasons, the maximum size of the ore is limited to about 8.0 mm).

Figure 16: Conceptual Drawing of DIOS Process (JISF)[14]



A fluidized bed reactor was selected for the prereduction step so as to avoid the necessity of agglomerating the ore. A low degree of reduction is easier to obtain in a fluidized bed reactor than a high degree of reduction, which fits the strategy of keeping the degree of prereduction low, about 20 percent, so as to not jeopardize the in-plant energy export which they need to maintain at 1 to 2 Gcal/thm. The consequence of this approach, of course, is lower efficiency of the smelting-reduction furnace.

The connecting of the prereduction and smelting-reduction furnaces is still a major problem to be overcome. The JISF plan to maximize the use of gravity for materials handling. Consequently, the prereduction furnace must be situated above the smelting-reduction furnace, making the structure very high.

The details of the cyclone shown in Figure 16 are complex and represent one of the key technologies in materials handling in this process.

Inert gas is used to weakly stir the iron melt while a top-blown oxygen jet stirs the slag layer. Aggressive stirring by the oxygen jet quickly increases coal usage. They are investigating the best arrangement for good stirring with low energy utilization.

The hot metal is saturated with carbon and contains less silicon than blast furnace hot metal; the sulfur content is a function of the fuel rate, fuel sulfur content and slag chemistry. The slag composition is similar to that of blast furnace slag, but is higher in FeO and MgO. The slag is suitable for cement applications.

Refractories are a big technical issue. Linings of Cr_2O_3/MgO have improved performance of the smelting-reduction furnace, but at high cost. A water-cooled lining is being considered to reduce refractory costs.

Most in-bath tests have used interrupted tapping similar to the tapping of a BOF. At their Fukuyama Works, NKK recently tested a single taphole (located at the slag/metal interface); a two-taphole approach is being considered. The determination of the best method to remove the molten products from the smelting-reduction furnace is considered to be a major unknown to be resolved prior to the commercialization of the DIOS process.

Raw Materials

Coal

In selecting coals for the DIOS process, the properties deemed important include:

- volatile matter content,
- ash analysis,
- ash fusion temperature,
- sulfur content,
- alkali content of ash,
- fluidity,
- moisture content, and
- transportability.

The JISF prefers low moisture coals because they result in lower fuel rates in the smelting-reduction furnace. (Dried coal has been used to date in the test work completed at NKK). Furthermore, they will attempt to use coal with a high volatile matter content in the DIOS process because they perceive this to be the least expensive coal. They will concentrate on cracking the volatile matter efficiently in the smelting-reduction furnace by post-combustion. However, this coal may not be all that desirable in smelting-reduction because of the energy penalties for the cracking of the volatile matter. The question of noncoking coals versus coking coals for the DIOS process has not been resolved since coking coals have not yet been tested. Coals containing 20 to 35 percent volatile matter have been evaluated in the current test program; the aim of the JISF is to expand the range of coals suitable for hot metal production. Coal blending is not being considered for the DIOS process. The aim coal rate is 800 kg/thm.

Ores

The ores to be charged to the DIOS process are sintering fines having a mean size of 2 to 3 mm. We were given some indication that they will attempt to increase the maximum ore particle size which can be processed by the DIOS process.[15]

Economic Considerations

The JISF has not published its estimates of capital costs to build a commercial DIOS plant, nor has it published its estimates of the operating costs of such a plant.

Concerning capital costs, the information released to us was in relative terms only, as noted below:

	Index
greenfield coke ovens/sinter plant/blast furnace	100
greenfield DIOS plant	80 to 85
blast furnace reline	25

For this cost information to be of any use at all, the size of the production units would have to be specified. We know that the Japanese are thinking big for the DIOS process; they are talking in terms of a 10 million tonne steel plant in which the blast furnaces are replaced with DIOS process units. To be fair, the JISF probably won't have any real capital cost figures to publish until the development work is completed on the 500 t/d pilot plant - sometime around 1995.

Obviously, the JISF is looking to the 500 t/d pilot plant to enable them to determine, with some accuracy, the operating costs of the DIOS process. The semi-commercial size of the pilot plant should assist them greatly in this regard.

As far as raw materials are concerned, the DIOS process would require essentially the same quantity of ore and fluxes as the blast furnace to produce one tonne of hot metal. Any difference would have to be in the amount of coal required by the respective processes. NKK supplied us with their estimate of energy utilization in the DIOS process compared to that of the conventional route to ironmaking, Table VI.

Table VI: Energy Utilization Comparison[16]

Process	Energy Utilization, Gcal/thm	
	Conventional	DIOS
Blast Furnace	2.8	-
Sinter Plant	0.7	-
Coke Ovens	0.6	-
DIOS*	-	<4.0**
Total Energy	4.2	<4.0

* smelting-reduction furnace (SRF) + prereduction furnace (PRF) + oxygen plant

** prereduction 15 percent; post-combustion 55 percent; temperature of charge materials to SRF 800°C; coal carbonization and gas reforming between SRF and PRF.

The energy export for both routes to hot metal is about equal at 1.3 Gcal/thm.

The JISF has set a target for post-combustion of 60 percent which would decrease the coal rate in the DIOS process. So far NKK has achieved 55 percent post-combustion.

Licensing Arrangements

Licensing arrangements have not been finalized; they are still several years away from having a proven, operating process to sell.

The JISF is the owner of all future developments regarding the DIOS process. Once the current pilot-scale program has been completed, around 1995, they believe that they will be in a position to design and build a 2000 t/d DIOS plant. The first such plant would most likely be built in Japan. When commercialization is deemed to be successful, the JISF will form a committee to market the technology.

Several member companies of the consortium, including Nippon Steel Corporation, Nippon Kokan KK, and Kobe Steel, Limited, would benefit from the sale of this technology through their role as construction companies in addition to being steel producers.

AISI DIRECT STEELMAKING PROCESS

The objective of the AISI Direct Steelmaking project is an energy-efficient, economically competitive, steelmaking process that will derive its advantages from the effective use of domestic raw materials, from continuous operation rather than batch, from avoidance of coke and the concerns over the environmental problems traditionally associated with coke ovens, from ease of start-up and shutdown, and from modularity in size to adapt to market conditions.[17] When it is implemented commercially, the process is expected to provide the following benefits:

- direct operating costs lower by US $11 to US $27 a tonne of steel produced, compared to the conventional route to steelmaking, i.e. coke ovens/blast furnace/BOF (energy cost savings, estimated at about 20 percent, included),
- lower cost of maintaining existing capacity by eliminating coke ovens which, because of environmental restrictions, are increasingly expensive to operate and/or replace,
- technical and economic improvements in steelmaking because of the continuous nature of the process,
- ownership position for the American steel industry in a new technology which has the possibility to become the next generation of steelmaking technology, and
- restoration, to the American steel industry, of a measure of leadership in technological development that has been lost in the past several decades.

Adoption of the new technology is touted to have positive social and economic effects for the USA as a whole in the ways listed below:

- lower cost to consumers of products made from steel,
- more efficient use of their nation's resources, by reducing the quantity of coal required to produce each tonne of steel, and of their nation's abundant supply of steel scrap,
- lower national energy consumption and, therefore, less reliance on foreign energy sources (The 20 percent cut in energy mentioned earlier represents seven percent of the total energy used by the primary metals industries of the USA.),
- elimination of the environmental problems which, historically, have been associated with coke ovens,
- reduction of the trade deficit of the USA by making its steel industry more competitive, and
- a stronger steel Industry, an industry that is vital to the defence and overall economic health of the nation.

Process Development

The AISI Direct Steelmaking project is the least developed of the four smelting-reduction processes being considered in depth; the research and development for this process is essentially just beginning. The progress to date is outlined below:

- 1986 - "The Steel Initiative" legislation was enacted by the US government to provide federal incentives for steel and other domestic metals industries to develop advanced technologies that could increase the energy efficiency and competitiveness of those industries,

- 1987, April - the Department of Energy (DOE) issued its Steel Initiative Management Plan which provided the framework for implementation of the program,

- 1987, August - AISI initiated a study to assess worldwide opinions and trends in developments in direct steelmaking,

- 1988, March - the study task force presented the AISI with a plan to develop a made-in-the-USA direct steelmaking process based on their findings,

- 1988, April - DOE issued its research plan which identified several key areas in which the steel industry could benefit from "leapfrog" technology, including a continuous ironmaking or steelmaking process,

- 1988, July - the AISI submitted to the DOE their research proposal for the development of a continuous steelmaking process based on in-bath smelting-reduction technology, with the expectation that sufficient government funding for the program would become available,

- 1988, October - the AISI proposal was accepted by the DOE for negotiation, and cofunding of costs incurred after November 29, 1988, was approved subject to the successful negotiation of a contract,

- 1988, December - the Congress enacted an amendment which substantially increased the funding for the Steel Initiative,

- 1989, May 25 - DOE approved the AISI/DOE Cooperative Agreement,

- 1990, February - the pilot plant for this process was under construction at Universal, Pennsylvania; the engineering of the pilot plant was by Hatch and Associates, and

- 1990, early June - the construction of the pilot plant facility at Universal was completed.

The pilot plant includes a 13.5-tonne smelting vessel designed for coal injection, oxygen blowing, and ore, pellet, or prereduced iron ore additions. The vessel is multi-ported to permit additions from the top, the sides, or the bottom. The pilot plant will be operated for 18 months to study a number of physical and chemical phenomena.[19] The key elements of the experimental program are delineated in Table VII.

Table VII: Key Elements of Experimental Program[18]

Issues	Experimental Program
Prereduction	• prereduction to FeO • coarse versus fine ores
Post-Combustion	• soft versus hard blowing • foam and emulsion stability
Heat Transfer	• fluid flow in converter as function of blowing and charging techniques • post-combustion • scale-up criteria
Productivity	• rate-limiting mechanism - foam stability - heat transfer - scale-up

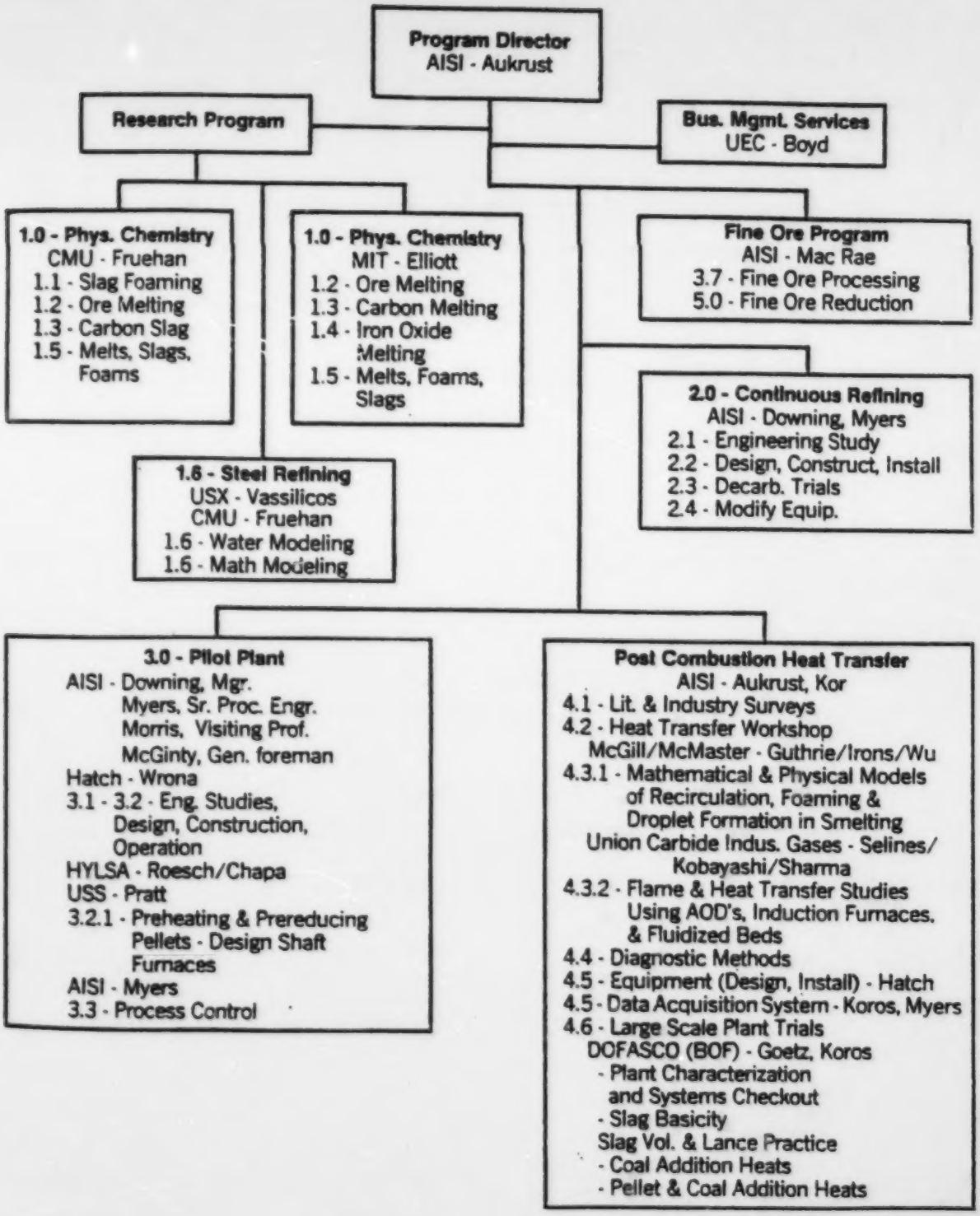
Research Program

The three-year, US $30 million, research program is a collaborative program with the US government, i.e. it is co-managed with both sides sharing the financial and technological risks and both sides partaking in the decision-making and problem-solving. It is, in fact, funded about 77 percent by the US government, 23 percent by the AISI.[18] It will define the technology and determine the economic feasibility of an in-bath smelting and refining process that could replace the current coke ovens/blast furnace/BOF steelmaking technology. Needed will be a full understanding of the chemical and physical processes at work when iron ore, coal, oxygen, and scrap are introduced into a smelter, as well as the means to control these processes effectively. Optimum designs and operating techniques will have to be developed for the smelter and associated equipment, including a preheating/prereduction furnace, gas cleaning equipment, smelter charging equipment, the equipment for continuous steel refining, and computerized process controls. It will also be necessary to solve, or project solutions to, the engineering problems involved in making the process work economically on a commercial scale.

The program, organized according to Figure 17, seems to be proceeding on schedule. The current status is as follows:

- the pilot plant construction is well under way with the melter start-up planned for the spring of 1990 (actual start-up, mid 1990),
- laboratory research is under way at Massachusetts Institute of Technology (MIT) and Carnegie-Mellon University, (CMU),
- continuous refining trials were held in the fall of 1989 at the pilot facility,
- large-scale post-combustion and heat transfer studies were carried out at Dofasco in the fall of 1989,
- program staff are coordinating the work of consultants who are developing a process model and a system for real-time computer process control,
- McGill and McMaster Universities will develop models, mathematical and physical, for the smelting-reduction process, and

Figure 17: Program Organization[17]


Program Director
AISI - Aukrust
Research Program
Bus. Mgmt. Services
UEC - Boyd
1.0 - Phys. Chemistry
CMU - Fruehan
1.1 - Slag Foaming
1.2 - Ore Melting
1.3 - Carbon Slag
1.5 - Melts, Slags, Foams
1.0 - Phys. Chemistry
MIT - Elliott
1.2 - Ore Melting
1.3 - Carbon Melting
1.4 - Iron Oxide Melting
1.5 - Melts, Foams, Slags
Fine Ore Program
AISI - Mac Rae
3.7 - Fine Ore Processing
5.0 - Fine Ore Reduction
2.0 - Continuous Refining
AISI - Downing, Myers
2.1 - Engineering Study
2.2 - Design, Construct, Install
2.3 - Decarb. Trials
2.4 - Modify Equip.
1.6 - Steel Refining
USX - Vassilicos
CMU - Fruehan
1.6 - Water Modeling
1.6 - Math Modeling
3.0 - Pilot Plant
AISI - Downing, Mgr.
Myers, Sr. Proc. Engr.
Morris, Visiting Prof.
McGinty, Gen. foreman
Hatch - Wrona
3.1 - 3.2 - Eng. Studies, Design, Construction, Operation
HYLSA - Roesch/Chapa
USS - Pratt
3.2.1 - Preheating & Prereducing Pellets - Design Shaft Furnaces
AISI - Myers
3.3 - Process Control
Post Combustion Heat Transfer
AISI - Aukrust, Kor
4.1 - Lit. & Industry Surveys
4.2 - Heat Transfer Workshop
McGill/McMaster - Guthrie/Irons/Wu
4.3.1 - Mathematical & Physical Models of Recirculation, Foaming & Droplet Formation in Smelting
Union Carbide Indus. Gases - Selines/Kobayashi/Sharma
4.3.2 - Flame & Heat Transfer Studies Using AOD's, Induction Furnaces, & Fluidized Beds
4.4 - Diagnostic Methods
4.5 - Equipment (Design, Install) - Hatch
4.5 - Data Acquisition System - Koros, Myers
4.6 - Large Scale Plant Trials
DOFASCO (BOF) - Goetz, Koros
- Plant Characterization and Systems Checkout
- Slag Basicity
Slag Vol. & Lance Practice
- Coal Addition Heats
- Pellet & Coal Addition Heats

- the Linde Division of Union Carbide will study post-combustion in the smelter vessel and heat transfer from post-combustion to the melt.

The research work is being leveraged by other industries with a stake in the success of the development work. North American Refractories Company is providing an engineer full-time during the trials as well as extensive testing and refractory development work. IBM has made available a one million dollar computer system and a joint study on automated decision-making using knowledge-based systems is being evaluated for potential joint sponsorship by AISI and IBM.[19]

Furthermore, AISI signed an agreement in October 1989 with HyLSA of Monterrey, Mexico, whereby HyLSA will research and develop the process to partially reduce iron ore pellets to wustite (FeO), the feed material for the envisioned direct steelmaking process. HyLSA's program includes trials in existing fixed and moving bed shaft furnaces (HyL I and III). This will provide information for the design of a prereduction shaft that could be located at the pilot plant to supply hot wustite to the smelter. Other elements of AISI's agreement with HyLSA include an evaluation of the metallurgical properties of wustite pellets and the production of a supply of wustite pellets for use in the start-up phase of the pilot plant smelter.[19] [How they will do this is questionable, since wustite is unstable below 560°C, decomposing to a mixture of α-iron in magnetite.]

If significant changes in the research plan are required, they will first be reviewed with the program's Board of Directors and, then, with their concurrence, with the DOE contracting officer and his technical representative. No significant changes will be adopted without negotiation with, and written acceptance from, the contracting officer. Such changes will be implemented by a modification to the Cooperative Agreement or Statement of Work as appropriate.

E. Aukrust, the Program Director, stresses that this is a research project. As such, the deliverables are:

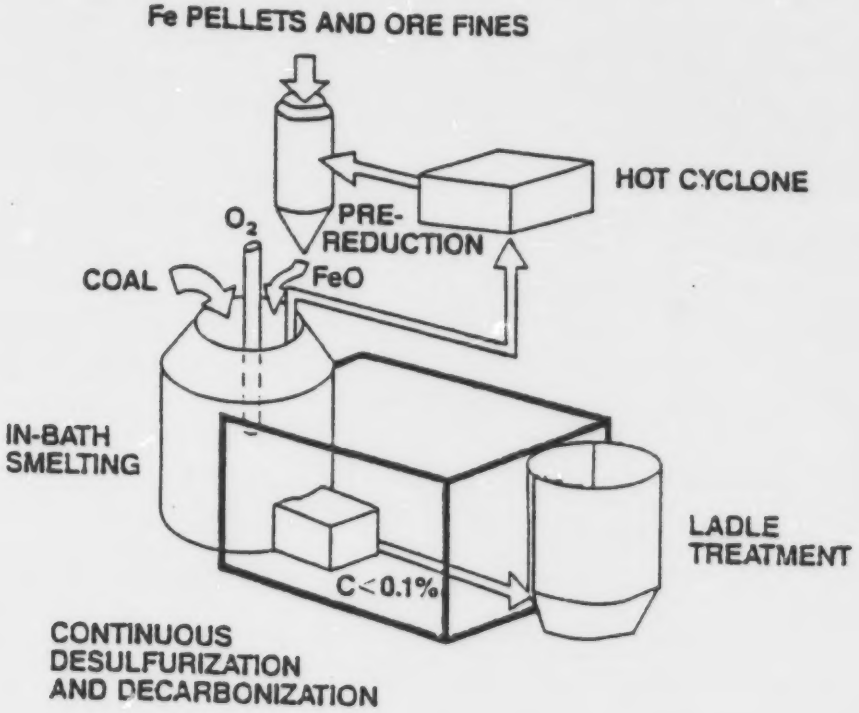
- a completed pilot plant program supported by extensive research designed to understand the smelting-reduction process,
- a study of scale-up and heat transfer,
- a study of post-combustion and heat transfer at Dofasco, and
- subcontracted effort by HyLSA, Mexico, on shaft reduction technology.

All of these parts to the program will come together in a techno-economic assessment of the viability of the process. This assessment will not include the engineering of, or a full-fledged plan for, a demonstration plant, but it will be the basis for a decision on whether or not to proceed with the next phase. Proceeding would mean a demonstration plant at a cost of more than US $100 million; cost sharing, it is anticipated, would be similar to the arrangements for the current pilot plant study.

Process Description

In the AISI Direct Steelmaking process, as currently envisioned, coal and ore, either raw or partially reduced, are charged into a vessel containing a liquid pool of crude iron. The mixture is injected with oxygen and the resulting heat and carbon monoxide facilitate the conversion of the ore to high carbon liquid steel. Further treatment with oxygen reduces the carbon content to the level required in the final steel product. Carbon monoxide given off in the process is burned inside the vessel to maintain a self-sustaining heat balance. The process flowsheet is shown in Figure 18.

Figure 18: Flowsheet of the AISI Direct Steelmaking Process[18]



The centerpiece of the process is the in-bath smelting of iron ore with coal and oxygen in a liquid iron bath. This technology draws on all areas of steelmaking developments of the last decade, including combined top and bottom blowing, the use and control of foaming slags, injection technology and the development of coal gasification in liquid melts which was researched extensively during the energy crises of the 1970s. Post-combustion of the gases exiting the iron/steel bath, with high efficiency of transferring the heat so generated back to the liquid bath, will be an integral part of the process. (It is crucial to its success.)

The hot off-gases from the smelting vessel will be used to preheat the ore and, if necessary, to prereduce it to FeO in a separate vessel.

The successful development of the AISI Direct Steelmaking process depends upon how well the project team can overcome the problems facing them in the smelting furnace, e.g. such problems as:

- efficiency of heat transfer from post-combustion to the melt, because:

    1. the heat is needed to drive the process, and
    2. otherwise, the off-gas temperature would be too high and the top of the reactor would burn out.

- controlled slag foaming, because:

    1. excessive slag limits the productivity of the smelting-reduction vessel; in this process, the specific gas evolution (Nm^3/t) is nearly 10 times higher than in a BOF and the slag volume is twice as high, resulting in a large volume of foamed slag, and
    2. insufficient slag foaming limits the rate of reduction in the smelting-reduction vessel; the rate of reduction is controlled by energy transfer in the liquid phases and depends on the three-phase (metal/slag/gas) fluid flow conditions in the reactor.

The task force faces these and many other challenges in bringing this process to a viable reality. Even so, they believe that by the year 2000 or 2010 they will have developed a technologically understood process. The statement was made that, by the year 2000, this process could be in operation in one or two minimills.[20]

Economic Considerations

With the final configuration of the process still unknown, no capital or operating cost estimates are available, nor will any be available for several years, in all likelihood.

The technology to be developed will belong to the AISI who will license the process. Although the license fees have not yet been set, licensing will apparently have a three-tiered structure:

- AISI member companies, USA - a modest sum,
- AISI member companies, non-USA - a somewhat higher fee, and
- all other companies - a still higher fee.

The purpose of the US Steel Initiative legislation, under which this process is being developed, is to put USA companies in the forefront of technology; profit from sales of technology is secondary. Nonetheless, the AISI will market the technology when it has been demonstrated to be successful and indications are that, most likely, the responsibility will fall to the AISI Counsel. A percentage of any licensing income will have to be returned to the DOE by the AISI, as spelled out in the Agreement.

BLAST FURNACE ENHANCEMENTS

The basic principles of blast furnace ironmaking have not changed from the time that liquid iron was first produced in a shaft-type furnace, the Stückofen, in Germany, in the early 14th century. Iron oxide, a solid reductant/fuel, and a flux are still charged into the top of the furnace, air is still pumped into the upper hearth of the furnace to burn the reductant/fuel to produce the hot reducing gases which ascend through the descending burden, carrying out the required thermal and chemical exchange with the burden materials, and molten iron and slag are still tapped from the bottom of the furnace.

What has happened to the blast furnace process, especially since the late 1950s, and is continuing today, is the enhancement of the process - by design of equipment, by improved efficiency, and by increased productivity.

The enhancements to the blast furnace ironmaking process which are pertinent to this study are listed in Table VIII (more details in Volume II).

Table VIII: Blast Furnace Enhancements

Enhancement	Developer/Practitioner
Coal Injection Intensive Coal Injection	Sidmar (and others) Thyssen Stahl (and others)
Combined Blast	Russia
Nitrogen-Free Blast Furnace The Floss Process	NKK (and others) Dr. mont Ferdinand Fink, Consultant
Oxy-Coal Blast Furnace Process	British Steel Corp/Hoogovens/Ilva
Pirogas	CRM/IRSID
The SIFF Process	Sacilor, IRSID
The TOP Process	IRSID-CIREP

Table IX shows the status of the enhancements noted in Table VIII.

Table IX: Status of Blast Furnace Enhancements

Enhancement	Status
Coal Injection Intensive Coal Injection	- commercial: many plants and spreading. Injection rates ~100 kg/thm - successful tests to 170-180 kg/thm injection rate; 160 kg/thm expected to be next "standard" level of injection
Combined Blast	- commercial and widespread in USSR - under test in USA
Nitrogen-Free Blast Furnace The Floss Process	- numerous paper studies - tested on 3.9 m^3 experimental blast furnace at NKK - patented - no evidence of any experimental work
Oxy-Coal Blast Furnace Process	- under test at BSC's Cleveland Works on 1000 t/day blast furnace
Pirogas	- commercial on at least two blast furnaces in France - no evidence of further work
The SIFF Process	- tested on no. 3 blast furnace (816 m^3) of Sacilor Rombas in 1983 - no evidence of further work
The TOP Process	- 5-day trial on Uckange blast furnace - much more work to be done

Of all the enhancements noted in Tables VIII and IX, the ones most likely to see widespread adoption between now and 2010 are coal injection, with increasing intensity of operation, and, possibly, combined blast. These will be discussed in some detail.

The Pirogas process needs the special provision of very low electricity prices, such as are available in France, particularly in the summer. This process is not likely to be adopted outside of France.

As for the other enhancements, should they be commercialized, they would not realize significant utilization for at least two decades. Notable by its absence from the list of enhancements is oil injection. Because of the oil price shocks of the 1970s, oil is viewed as not a viable injectant in most countries. Thus, although it does continue to be used on some blast furnaces, oil injection is expected to continue to decline in importance.

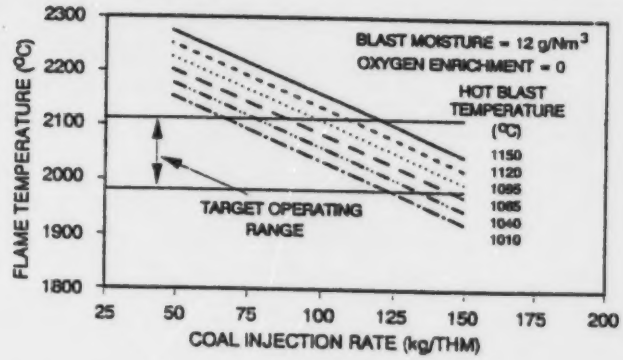
COAL INJECTION

Coal injection into the blast furnace has been practiced actively since the 1960s, at least on a few furnaces. More recently, however, numerous IISI member companies have adopted coal injection on more than 60 blast furnaces, with another 15 installations planned over the next two years. A number of blast furnaces in the USSR, China, and other Eastern Block countries are equipped to inject coal through the tuyeres. Coal injection rates vary widely, ranging from about 32 to about 140 kg/thm with tests completed successfully at higher injection rates.

In all cases in which the injection rate exceeds 100 kg/thm, hot blast temperatures higher than 1100°C and/or oxygen enrichment are employed. This practice probably stems from the use of the raceway adiabatic flame temperature (RAFT) criteria and limiting carbon/oxygen ratios at the tuyeres to guide furnace operations.

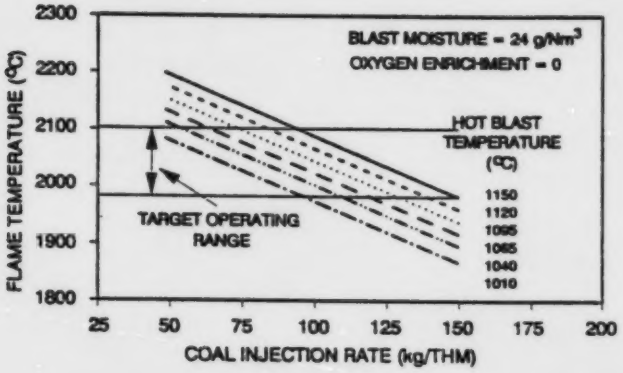
Figures 19 and 20 relate the injection rate of a high volatile coal to the RAFT at two levels of blast moisture. With natural humidity, 12 g/Nm^3, and a hot blast temperature of 1080°C, a coal injection rate of 150 kg/thm could be attained while maintaining a minimum RAFT of 1980°C (Figure 19).

Figure 19: RAFT-Based Coal Injection Rate at Natural Humidity[21]



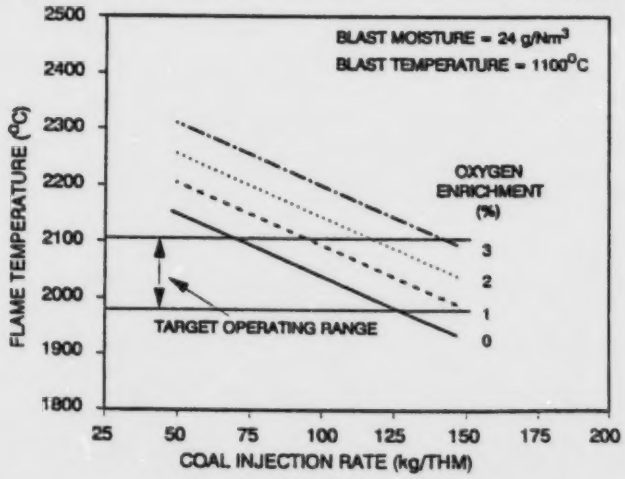
Frequently, some steam is added to the hot blast, regardless of the level of injection, to effect a smooth burden descent. Figure 20 is presented to show the effect of a higher blast moisture, 24 g/Nm^3, on the coal injection practice. In this case, all else remaining equal, a coal injection rate of about 125 kg/thm can be achieved while maintaining the same minimum RAFT of 1980°C.

Figure 20: RAFT-Based Coal Injection Rate with Steam in Blast[21]



The impact of oxygen enrichment on the RAFT is shown in Figure 21. From RAFT limitations, a one percent increase in the oxygen content of the hot blast permits the coal injection rate to be increased by almost 25 kg/thm.

Figure 21: RAFT-Based Coal Injection Rate with Oxygen[21]



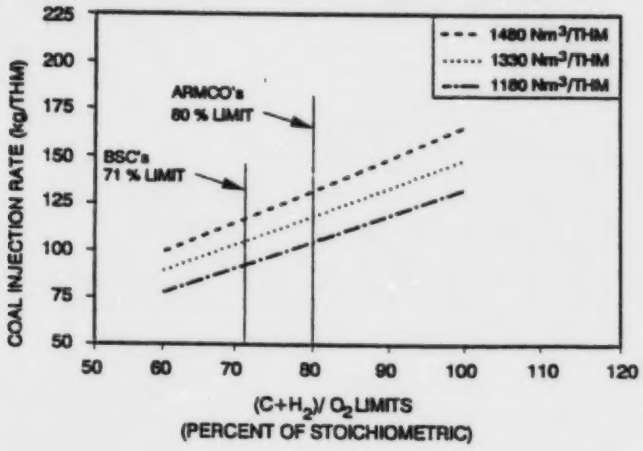
Oxygen enrichment is used primarily to offset the loss in productivity which results from an injection rate that is not fully compensated for by blast condition adjustments. It also has importance in increasing the amount of oxygen available to burn the carbon supplied by the injected coal.

The maximum injection level of a hydrocarbon into the blast furnace is generally governed by a limiting carbon:oxygen ratio at the tuyeres. Many experimental simulations have been carried out to determine what this limit might be, but actual operating experience has suggested empirical values. Armco estimates that a pulverized coal injection rate should not exceed 80 percent of the stoichiometric ratio of $(C+H_2):O_2$ to form CO_2 and H_2O before exiting the tuyeres. British Steel Corporation (BSC), using granular coal, suggests that 40 percent excess oxygen should be available above the stoichiometric requirement to form CO_2 and H_2O. Expressing the BSC limit the Armco way results in a limit of 71 percent of the stoichiometric ratio of $(C+H_2):O_2$ to form CO_2 and H_2O

for the granular coal injection process. These criteria were developed in the full realization that only CO and H_2 (and N_2) exist in the raceway in front of the tuyeres.

Figure 22 shows the relationship between possible coal injection rates and the stoichiometric balance to form CO_2 and H_2O at the tuyeres, at three specific wind rates (Nm^3 wind/thm).

Figure 22: Stoichiometric Limitations on Coal Injection[21]



At 80 percent of stoichiometry, pulverized coal can be injected at the rate of 133 kg/thm when operating at a specific wind rate of 1480 Nm^3/thm, a relatively low level of furnace efficiency. Approximately 105 kg/thm can be injected at 1180 Nm^3/thm, an increased level of furnace efficiency.

The BSC oxygen rule for granular coal results in a maximum coal injection rate of 118 kg/thm when blowing 1480 Nm^3/thm and 90 kg/thm when operating with a more efficient practice of 1180 Nm^3/thm.

Oxygen enrichment extends the limit of coal injection by decreasing the $(C+H_2):O_2$ ratio at the tuyeres for a given wind rate. Each one percent increase in oxygen added to the blast air permits the injection of an additional 6 to 8 kg of high volatile coal per tonne of hot metal.

The injection of coal having a lower H_2 content also lowers the $(C+H_2):O_2$ ratio at the tuyeres. However, a lower H_2 content may detract from the coal's ability to devolatilize rapidly (essentially particle explosion), thereby slowing the rate of combustion. The interrelationships among the coal volatile matter level, coke replacement ratio, and maximum coal injection rate are not completely understood by many coal injection users.

A complicating factor which appears to lower the coal injection limit is variability of the wind rate from tuyere to tuyere. Clearly, if wind rate imbalances of, for example, 10 percent occur, the overall coal injection rate limit would be lowered by 10 percent.

To successfully achieve a high coal injection rate, tuyere wind rate measurements are recommended. A simple system which measures the pressure drop (ΔP) between the bustle pipe and each tuyere would allow the operator to ensure that the ratio $(C+H_2):O_2$ is within prescribed limits. Furthermore, the ΔP measurements provide the basis for a safety system to ensure that coal is not blown into the bustle pipe should the tuyere become blocked momentarily. Two companies, Hoogovens and BSC, have experienced fires in the bustle pipe because of tuyere blockages. To prevent a recurrence of the fire, both companies have placed thermocouples in the bustle pipe to ensure that the bustle pipe gas temperature does not exceed the hot blast temperature. BSC has also

added individual tuyere wind rate measurement based on differential pressure; coal injection to individual tuyeres is suspended if the ΔP and, hence, the wind rate fall below the prescribed level.

Coal Properties and Selection

A wide range of coals, from lignites to anthracites, has been injected successfully. For economic reasons, the grade of coal should be at least equal to that of the coke it is replacing - from the viewpoints of ash and sulfur contents.

Tar and Soot Formation Properties

The relationship between coal rank, as measured by the specific volatile index (SVI), and the propensity of the coal to generate tar upon being heated is shown in Figure 23.

Figure 23: Approximate Quantity of Tar from Various Coals[22]

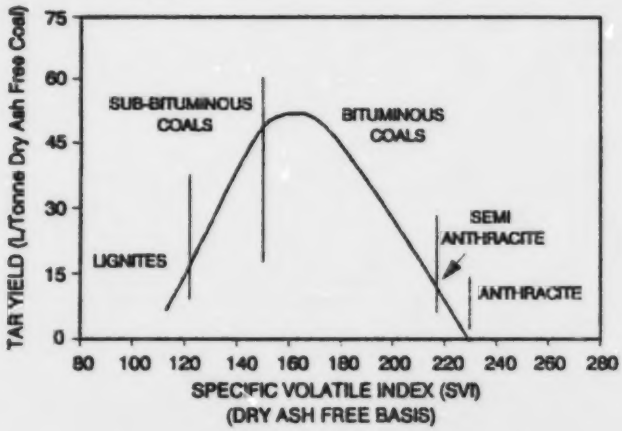


Figure 23 indicates the peak of tar evolution to be in the bituminous coal range; a high volatile Pittsburgh seam coal, for example, would be at this peak.

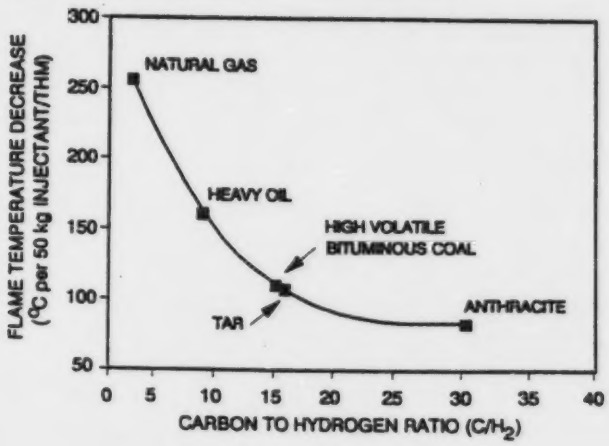
In selecting a coal for injection into the blast furnace, a high volatile, high grade, steam coal is a strong candidate. However, coal of this type must be injected at less than the limit imposed by stoichiometry discussed earlier, so that the tar-forming substances do not crack in the raceways and form soot. Ideally, at very high injection rates, a coal closer to anthracite, or a blend of high volatile and high SVI coals should be selected. Confirmation of this statement is found in the experience of the Chinese with very high levels of anthracite injection.

Other Coal Characteristics

Several companies have reported having difficulties with some coals. The very high ash coals contribute to buildup in the tuyeres. High free swelling index coals tend to stick together and to hot surfaces, thereby contributing to blockages. The most common difficulty, blockages in the coal lines, occurred when coals having greater than 1-1/2 percent moisture entered the system.

One final characteristic, common to coal and other hydrocarbons, that influences the injection rate is the $C:H_2$ ratio. Figure 24 shows the relationship between the $C:H_2$ ratio and the RAFT of a blast furnace.

Figure 24: $C:H_2$ Ratio Influence on RAFT[21]



Coal Injection Systems

Coal injection is practiced widely in IISI member companies. A summary of supplier companies currently providing coal injection systems and/or know-how is given in Table X.

Table X: Summary of Coal Injection Suppliers

Supplier Company	No. of Furnaces		Injection Rate (kg/thm)
	Equipped	Planned	
Paul Wurth/Kuttner	14	5	60 to 140
Armco, Armco/NSC*	16	3	35 to 140
Klöckner	4	-	90 to 110
Kobelco	4	1	67 to 117
Kawasaki/Denka	4	-	16 to 121
Simon Macawber	3	3	80 to 117
Sumitomo	2	-	43 to 104
Acesita	2	-	120
Godo	1	-	59 to 64
Sollac	-	1	
Supplier Unknown		2	

* NSC = Nippon Steel Corporation 1989/90 data

Eastern Block countries have many furnaces equipped with coal injection. Licensentorg, in the USSR, and Koste, in East Germany, supply technology; however, their technology appears to be inferior to that of the Western industrial leaders. Shoudo Iron and Steel Company of the Peoples Republic of China has vast experience, but Chinese companies are not noted for their ability to supply and engineer facilities to meet Western standards.

Table XI attempts to classify coal injection systems at their various stages of development. It also lists each supplier according to this classification.

Table XI: Classification of Coal Injection Systems

Generation		
First	**Second**	**Third**
Various non-dedicated coal preparation systems. Separate pulverization and drying.	Independent coal preparation plant, combined pulverization and drying.	Independent coal preparation plant, combined pulverization and drying.
Short distance pneumatic delivery from coal storage to coal injection tanks at a single furnace.	Pneumatic single line coal delivery to injection systems at one or more furnaces.	Pneumatic single line coal delivery to injection systems at one or more furnaces.
Various mechanically controlled coal feed systems to individual coal lines.	Mechanically controlled coal feed (rotary valves, screw conveyors) to individual coal lines.	Pneumatic single line coal delivery to a splitter/distributor close to bustle pipe.
Low density coal feed to individual tuyeres.	Multi-pneumatic coal delivery lines to individual tuyeres.	Dense phase coal delivery from distributor through lines to each tuyere.
Suppliers		
Early - Paul Wurth - Armco - Petrocarb (pre-Kobelco)	Klöckner, Armco, Paul Wurth, Kobelco, Sumitomo, Acesita, Godo, Simon Macawber, Kawasaki/Denka, Sollac, Koste, Russian, Chinese	Klöckner, Armco, Paul Wurth/Kuttner

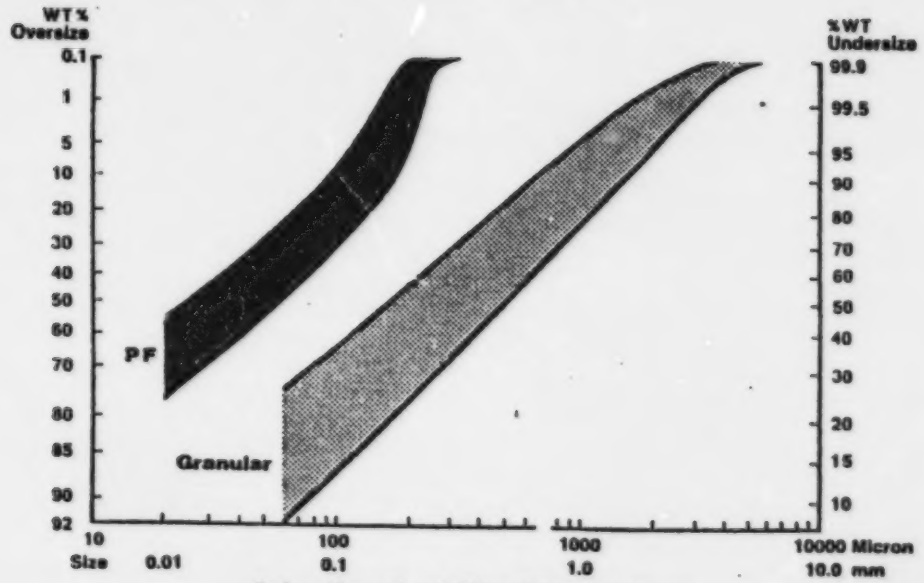
Three of the supplier companies listed in Table X can be eliminated as serious sources of coal injection systems. Godo does not appear to be actively marketing their technology. The Sollac system is based on coarse coal, 100 percent <3 mm, which would limit the rate of coal injection. Acesita, in Brazil, base their technology on mechanical rotary valves similar to the first generation injectors used by Paul Wurth. Paul Wurth has since moved to a fully pneumatic system developed in conjunction with Kuttner.

Review of Competing Technologies

BSC/Simon Macawber

BSC/Simon Macawber has indicated a number of benefits for granular coal injection (GCI) over pulverized coal injection (PCI). They have stated that granular coal is safer to handle than pulverized coal, but this statement is belied by the fact that granular coal does contain fines which may cause an explosion (Figure 25).

Figure 25: Particle Size Distribution of Injection Coal[23]



(note: PF = pulverized fuel, i.e. PCI)

The safety of GCI was supposedly enhanced by being able to inject the coal in the moist state - which also saved the drying costs. However, owing to operational difficulties, BSC has gone to coal drying (<1.5% H_2O) like all its competitors. The statement that GCI requires less grinding than PCI seems to be valid, but the difference in grinding cost appears to be minor in the overall situation and these small savings may even be offset by wear in the injection system.

Other factors which tend to mitigate against the use of the Simon Macawber GCI system include:

- the system is mechanically based, requiring at least one screw conveyor and one motor for each pair of tuyeres - contributing to higher maintenance costs,
- to achieve modest levels of coal injection (>70 kg/thm) with low blast temperatures, the BSC operators have used substantial amounts of oxygen - which may be unnecessary for the PCI systems with their finer coal size,
- lance changing equipment is lacking so that line blockages or motor failures result in the loss of an injection lance due to the lost cooling effect of the coal as it is being injected; coal injection cannot be restored at these tuyeres until the furnace has been shut down for lance replacement.

Operating staff at BSC (especially at Ravenscraig) have some concerns with their coal injection system; however, the Corporation still markets the technology because, according to competitors, senior management insists that they do so.[21]

The investment for a Simon Macawber GCI system can be matched or bettered by advanced PCI system suppliers.

Armco's PCI System

Armco has the longest continuous history of any steel company in the field of coal injection. This long experience and the dependability of the technology appear to be the main reasons why companies in Japan, Korea, and the Netherlands have opted for the Armco system. However, this technology does appear to have some deficiencies such as the following:

- to equalize the pressure drop in each injection line, the coal distributor is located above the blast furnace (to balance the length of, and number of bends in, the injection lines to each tuyere), and
- this injection system requires three injection vessels a furnace, one of which is always on standby as protection against system interruptions from the frequent line blockages.

In general, the Armco system is stated to be dependable. However, the extra equipment and the injection lines appear to result in a system which is substantially more costly to purchase and operate than those of Paul Wurth and Klöckner.

Sumitomo's PCI System

The Sumitomo approach is similar to the Paul Wurth second generation technology - using a unique distribution system to deliver exact amounts of coal to each tuyere. The coal is split from one line to four lines, each of which is split again to seven lines so as to supply 28 tuyeres. The use of this cumbersome technique and mechanical rotary feed valves contributes to the high cost of this system.

Kobelco and Kawasaki/Denka PCI Systems

The Kobelco and Kawasaki/Denka systems are quite similar, both being based on the earlier Petrocarb approach. These systems are entirely pneumatic, but of the second generation type. Instead of a simple coal distributor, which is employed by the most advanced systems, these companies use multiple lines from the injection vessels all the way to the individual tuyeres. Both systems appear to be dependable, but are in a higher cost category. Maintenance of the complex piping network also appears to be costly.

Klöckner Stahltechnik PCI System

Klöckner has broad experience in conveying materials pneumatically for many metallurgical purposes. Their coal injection system appears to be well-engineered, employing sensibly designed valving, enabling easy maintenance. While Klöckner can supply various coal injection systems, they favor and recommend the third generation approach which leads to the lowest cost. This system can deliver coal at various degrees of coarseness, but Klöckner prefers PCI. Klöckner appears to be competitive and is attempting to overtake its chief competitor, Paul Wurth/Kuttner. These rivals, along with Armco, have evolved similar technologies. Klöckner's delivery time from contract signing to commissioning, 15 months, was the shortest quoted - up to six months less than for competing systems.

Paul Wurth/Kuttner System

Paul Wurth, prior to its cooperation with Kuttner, sold a system based on mechanical rotary valves to control the coal feed to the individual tuyeres. The addition of Kuttner's dense-phase, pneumatic transport technology and the development of a coal delivery splitter allowed Paul Wurth to move into third generation technology. In 1986, Klöckner won a Sollac-Dunkerque installation away from Paul

Wurth while Paul Wurth was in the transition period. (Sollac-Dunkerque had previously equipped two blast furnaces with Paul Wurth equipment.) In June 1988, this situation was reversed when Paul Wurth won the contract for the two blast furnaces at Sollac Fos-sur-Mer. Paul Wurth is once again one of the leaders in coal injection technology.

Economic Considerations

Investment Requirement ($ 1988/89)

Coal injection technology has evolved rapidly in recent years. The investment costs, as noted by A. Poos, CRM, have decreased by about 30 percent over the past five years. He also points out that the coal injection technologies appear to be converging towards a similar design.[24]

The actual investment cost will be different at each plant. However, some generalities can be expressed. Gathergood quotes an investment range of US $60 to US $100 an annual tonne of coal injected, depending upon plant sizes, type of system, and sophistication of control. SSAB, at Luleå, which was the first plant to install a Klöckner system, found the Armco and Kobelco systems too costly. They opted for the Klöckner technology, partly because it appeared to be technologically viable, and partly because of special pricing arrangements which would allow Klöckner to capitalize on this plant as a demonstration unit. SSAB has since built a two-furnace system at their Oxelösund plant with Klöckner as the supplier.

Systems without a coal preparation plant would cost US $46 to US $57, according to Simon Macawber and Paul Wurth, respectively. Complete systems, including coal preparation, range in cost from US $60 to US $75 an annual tonne of coal for a range of plant sizes from 570 000 down to 165 000 tonnes of coal a year, respectively. The highest investment noted was for a sophisticated system, using Armco technology, installed at Hoogovens; this plant cost US $95 an annual tonne of coal injected. The simple payback time reported by various companies ranged from 18 months to 2.5 years, depending mainly on the capacity of the coal injection system. The time required from the initiation of a study to the commencement of coal injection has been quoted at 16 months to two years.

Operating and Maintenance Costs

The current leading systems are all pneumatic, requiring only the extension of the duties of existing operating personnel to operate the system. The only exceptions, in which additional labor was required, were at Hoogovens and at Posco (both Armco systems) where a staff increase of one man a shift was required to operate the facilities. The costs of utilities, transport and drying gases are, themselves, site-specific, but there is little reason to expect differences among the leading pneumatic systems.

Total maintenance costs are sketchy. However, one plant, with a third generation system did report maintenance costs between US $2.00 and US $3.00 a tonne of coal injected.

Future

The main emphasis, particularly in Europe and Japan, appears to be towards increasing the coal injection rates. The design of the injection system seems to have stabilized.

While many blast furnaces are far from it, the current general goal in Europe is a coal injection rate of about 160 kg/thm; the next goal is injection at the 200 kg/thm rate. Coal injection rates between 160 kg/thm and 200 kg/thm, assisted by oxygen enrichment, are expected to achieve commercial reality

before 2010, on a fairly broad basis. Some blast furnaces may even be operating at higher levels of coal injection; such operations entail problems to be overcome, besides having great potential.[25] Concern for the unknown is expressed in many quarters, i.e. what is the lowest viable coke rate?, what changes in coke properties will be required at the low coke rates anticipated?, etc.

The technology leaders, Thyssen Stahl, Hoogovens, BSC, and Sollac, are all evolving intensive blast furnace coal injection practices and appear, for the most part, to be freely providing knowledge of their progress. European Coal and Steel Community (ECSC) studies are being carried out in the area of oxy-coal blast furnace operation; BSC, Hoogovens, and Ilva are developing the technology to inject up to 400 kg coal/thm on a nominally 1000 thm/day blast furnace at BSC's Cleveland Works. This work should provide some valuable answers regarding the future (beyond 2010) potential levels of coal injection.

COMBINED BLAST

The term "combined blast" refers to the simultaneous injection of oxygen-enriched hot blast and natural gas into a blast furnace.

Natural gas and oxygen have an opposite influence on the temperature conditions and gas-dynamic conditions within the blast furnace hearth. Oxygen increases the RAFT, while decreasing the quantity of combustion products (compared to the equivalent air combustion). Natural gas decreases the RAFT because, per unit of oxygen consumed in combustion, the heat release from natural gas in the raceway is about 30 percent of that from coke; however, the volume of combustion products (CO and H_2) is approximately twice that from burning coke.

Theoretically, the temperature and quantity of the combustion products will remain constant with increasing oxygen enrichment if natural gas injection is maintained at 0.65 to. 0.70 Nm^3/Nm^3 oxygen.[26]

Combined blast operation carries the following features:

- a substantial increase in the concentration of reducing gases formed at the tuyeres (by 1.5 to 1.7 times), resulting in
- increased indirect reduction of the iron ore (as characterized by the reactions $Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$ and $Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$) and
- decreased direct reduction of the iron ore (as characterized by the reaction $Fe_2O_3 + 3C \rightarrow 2Fe + 3CO$),
- increased H_2 in the reducing gases; H_2 is a better reductant than CO above 810°C, and
- higher utilization of the reducing potential of the H_2 and CO, resulting in
- a significant decrease in coke rate and
- a sharp increase in smelting intensity.

Calculations geared to the conditions of the Novolipetsk Iron and Steel Works indicated that the minimum coke rate and maximum blast furnace productivity would be achieved with 43 percent oxygen in the hot blast, when direct reduction approaches zero. Any subsequent increase in the oxygen content of the hot blast would result in a higher coke rate while the productivity would remain essentially constant.

Initial work on combined blast began in the USSR in the 1950s, starting at 24.3 percent oxygen concentration in the hot blast. The enrichment oxygen was delivered to the suction side of the blowers, while natural gas was injected through the tuyeres. Other tests followed. The Iron and Steel Institute and the Novolipetsk Iron and Steel Works carried out a series of long-term smelting operations with blast oxygen concentrations of 35 to 38 percent; these tests paved the way to commercializing this technology and to evaluating the prospects of extending its limits.

The testing/development of combined blast technology required preliminary preparatory work with the aim of ensuring the faultless functioning of the various furnace systems and equipment, including:

- improved method of introducing oxygen into the blast,
- increased safety of the turboblowers and blast furnace equipment operation,
- increased capacity of burden handling and charging system and of the natural gas supply mains, and
- modified design of injection device.

At 35 percent oxygen, specific consumption of oxygen totaled 200 Nm^3/thm and of natural gas, 153 Nm^3/thm. Some adjustment to the burden distribution was required to counter the tendency towards increasing peripheral gas flow with increasing combined blast.

Combined blast is used widely in the USSR, accounting for >90 percent of the hot metal production. The highest oxygen concentrations in the blast (31.4 to 33.3 percent) and specific natural gas consumption (140 to 155 Nm^3/thm) are used at the Novolipetsk and Cherepovets Iron and Steel Works. Combined blast was tested at 40 percent oxygen in 1980 on a blast furnace of the Novolipetsk Iron and Steel Works. The effectiveness of the combined blast apparently increases with the level of preparation of the iron-bearing raw materials.

In 1971, Stelco Inc. tested combined blast on "C" blast furnace at Hilton Works, Hamilton, Ontario.[27] The maximum sustainable oxygen enrichment was 27 percent oxygen in the hot blast; the corresponding natural gas injection amounted to about 75 kg/thm.

The limitation was not in the process but in the equipment. This relatively small (7.5 m hearth diameter) blast furnace was equipped with a standard 2-bell McKee top. When the oxygen enrichment was increased to 28 percent of the hot blast, with the appropriate increase in natural gas injection, the steam injected between the bells for flame suppression was inadequate and a fire broke out at the furnace top which required three skips of water to quench. A sealed top, such as is required to operate with high top pressure (common mode of operation in the USSR), would be required to operate with levels of oxygen enrichment above 27 percent using natural gas injection.

The results of the Stelco tests are summarized below:

- hot metal production increased at the rate of 2.7 percent for every percent of enrichment, i.e. by 1.2 thm/t oxygen (99.5 percent oxygen),
- the coke replacement ratio was 0.85, i.e. every kg natural gas/thm saved 0.85 kg coke/thm,
- the process limit of combined blast operation was not reached.

Thus, high levels of combined blast are another alternative to lower coke consumption in the blast furnace - provided the economics are right. This approach is being studied in the USA. The Gas Research Institute[28] and East Ohio Gas Company[29] are deeply involved.

1. An operating blast furnace (8.5 m hearth diameter)) at Warren Consolidated Industries has operated for sustained periods with levels of injection exceeding 75 kg/thm, and for shorter periods at levels of 85 kg/thm.[30] Natural gas consumption was 77 Nm^3/104 Nm^3 oxygen or 0.74:1.0.

2. Tests with high levels of natural gas are planned on no. 3 blast furnace at Armco's Middletown Works. The Gas Research Institute will be involved. Natural gas injection levels of up to 125 kg/thm are the aim; the target date to achieve this level (through staged increases), is spring 1991.

3. LTV, Cleveland Works, has achieved a natural gas injection level of 90 kg/thm.

Some countries, or some parts of some countries, may have sufficient natural gas supplies at a price which makes high levels of natural gas injection economically justifiable. These situations bear exploiting if they fit the needs of the steel plant, especially since high levels of natural gas injection substantially substitute H_2 for CO in the reducing gases, leading to lower CO_2 ("greenhouse gas") emissions. However, in the longer term, and for the maximum replacement of coke in the blast furnace process, coal injection appears to be virtually inevitable.

COKING TECHNOLOGY

Coke

Coke is the major source of energy and reductant in the production of iron in the blast furnace; as long as there are blast furnaces, coke will be needed. Consequently, coke oven batteries are a critical part of the integrated steel industry. There exists no viable alternative to coke ovens, nor is any anticipated before at least the turn of the century, if then. Both the coke producer and the coke user, therefore, will continue to be concerned with the production and availability of coke of the desired quality produced economically in an environmentally acceptable manner.

High quality blast furnace coke has the following characteristics:

- low ash, with only minor contents of troublesome elements such as sodium, potassium, phosphorous, and zinc,
- low sulfur,
- strength sufficient to maintain its size during handling and descent in the blast furnace, and
- lump size large enough to guarantee permeability of the burden in the blast furnace.

Typical specifications are given in Table XII.

Table XII: Typical High Quality Coke Specifications[31]

Item	Specification	Effect
Ash (%) Sulfur (%) $K_2O + Na_2O$ (%)	<8.0 <0.7 <0.2	+1% Ash = +15 kg/thm coke rate +0.1% Sulfur = +2.5 to +4 kg/thm coke rate Recycle load above 3 kg/thm causes premature coke breakdown, slipping, etc
Stability	>58 (wharf) >60 (stockshed)	+1 Stability unit = -3 to -8 kg/thm coke rate
Size	>3/4in	+10% plus 1½in = -5.5 kg/thm coke rate = +1% productivity
Coke Strength after reaction (CSR)	>57.5	+1 CSR below 57.5 = -1.5 kg/thm coke rate +1 CSR above 57.5 = -0.3 kg/thm coke rate

Cokemaking

The coke plant operator produces coke of the quality, and in the quantity, required by the blast furnace operation, respecting any limitations imposed by his plant's age and design. He cannot risk the integrity of his operation and he faces ever more stringent environmental and industrial hygiene regulations. However, even thus constrained, the cokemaker has considerable leeway to positively impact the blast furnace operation. He can tune his batteries to maximize coke quality, effect better control of his ovens to minimize variations in product quality, maximize his by-product credits to make the coke less costly, and capitalize on coal market opportunities to lower the cost of incoming coals. He can also maximize the life of his batteries through thoroughly disciplined operation and maintenance.

In Europe, the only work on the coking process of any magnitude is being carried out by Ruhrkohle with Bergbauforschung and, to some extent, with German coke oven builders. In Japan, several of the steel companies, including Kobe, Nippon Kokan, and Nippon Steel, are working on new coking processes, but none would talk about its efforts in this direction.

In Japan, a fundamental research study of the next generation of coking processes is to begin in 1990. This will be a national effort funded by the Iron and Steel Institute of Japan (Japanese steel companies) and is expected to last three years. The targets of a new coking process are to be defined in this study; both modifications to the current process and entirely new processes will be considered. This research will be conducted by Professors Muchida and Ohtani of Kyushu University, Professor Salada of Hokaido University, and one professor from Tohoku University. The outcome of this effort will likely be a National Initiative to develop and prove the next generation of cokemaking technology. No estimate of the time to a viable process was given but it is unlikely to be past the pilot/demonstration stage before at least the turn of the century.

Technology that the developers were willing to discuss include:

- current coke oven design (essentially wider ovens),
- the jumbo coking reactor, and
- the Japan Iron and Steel Federation's formed coke process.

These technologies will be discussed in some detail on the following pages.

CURRENT COKE OVENS

Coke oven batteries have changed very little over the past half century. The significant differences in modern batteries are limited to size, control and antipollution equipment. As modern blast furnace practice demanded ever higher coke quality, the coke producers were forced to modify coal blend strategies, redefine the safe limits of battery operations, and consider such technologies as blend additives, selective pulverization, preheating, partial briquetting, bulk density control, programmed heating, dry quenching, etc.[32,33]

The modern coke oven has forced a major rethinking of oven wall and flue design. A typical post-war (WW 2) coke oven was between 3.5 and 4.0 metres in height. During the 1960s, battery designers, looking to improve the economics of cokemaking, engineered taller, longer, coke ovens; 5.0 and 6.0 metre coke ovens became common. By the late 1970s, battery heights approached 7.0 and 8.0 metres. The normal 70 mm taper of the coking chamber from pusher side to coke side requires a horizontal temperature distribution to compensate the changing width of the coal charge. The energy distribution problems, therefore, became two-dimensional, and the correct heating of tall batteries became the subject of many research investigations.

Increasing the oven volume by increasing the width was considered to be uneconomic because of the anticipated disproportionate loss in specific output and the associated increase in capital cost. It was also rejected because of anticipated deterioration in coke quality. However, an increase in width, in terms of structural design, was viewed as being advantageous.

Previous studies on the loss in specific output created by an increase in coke oven width had indicated very unfavorable results. However, extensive research work in West Germany during the 1970s established just the opposite.

True, wider ovens lead to a reduction in average coking rate, with a consequent drop in specific output. Today, however, various feasible solutions are available, such as improved heating, different brick composition, and the charging of dry coal, to compensate for these losses and to further improve the economic efficiency of wider ovens. Additionally, studies conducted on an operational scale verified that wider ovens have no detrimental effect on coke quality.

Examples of the first step towards adopting wider coke oven technology are two large-scale modernization projects in West Germany. The first project was the Huckingen coke plant of Mannesmannröhren-Werke AG (550 mm wide); the second was the Prosper coke plant of Ruhrkohle AG (590 mm wide). (Up to this time, the width of the coking chamber had been around 450 mm.) Both projects were similar and so only the Prosper plant[34] will be discussed.

The previous Prosper coke plant had a capacity of approximately two million tonnes a year and consisted of eight batteries, with a total of 360 small ovens, each 4.1 x 13.8 x 0.45 metres. The facilities were obsolete and called for substantial capital investment within eight to ten years to replace all the batteries so as to secure and warrant the continued operation of the plant.

Since the Prosper plant was intended to be operated far beyond the year 2000, Ruhrkohle AG considered the potential for ensuring, in the long term, a low-cost and environmentally compatible coke plant operation by implementing advanced technology and exhausting all rationalization possibilities.

The existing infrastructure and ancillary installations could be adapted and utilized for the planning of the new coke plant. Thus, the planning was concentrated on the coke oven portion. To optimize the plant, a study was made to determine whether the installation of high-capacity ovens would bring about a substantial structural improvement, savings in labor costs, and more favorable conditions for environmental protection. Planning had to be based on the following criteria:

- a capacity of 5600 t/day and/or approximately two million tonnes a year dry coke should be maintained,
- the layout of the coke oven batteries had to consider certain restrictions, e.g. oven length could not exceed 16.6 m, for space-related reasons, and oven height could not exceed 7.0 m for heat supply reasons (underfiring with coke oven gas), and
- economic advantages obtained by the plant restructuring had to be on such a scale that the additional capital investment, if any, would be economically justifiable.

Comparison of three alternatives considered by Ruhrkohle for the Prosper plant showed that the economical operation of the coke plant could be assured over a relatively long term by building three, modern, large-capacity batteries with 50 ovens each, having oven dimensions of 7.1 x 16.6 x 0.59 m and a working volume of 62.3 m^3. At the same time it was possible to create better conditions for the implementation of environmental protection measures. The result of this profitability analysis, together with the anticipated operational advantages, led to the decision to proceed. Moreover, Ruhrkohle decided to install coke dry quenching (CDQ) facilities for the entire Prosper coke plant in conjunction with the construction of the third battery at an additional investment of US $60 million. (Coke dry quenching is mandatory in Germany under TAL* 86, The Clean Air Act, for environmental reasons for the operation of new coke oven plants.[35])

The operating results proved the efficacy of the new approach. The first operating results from the Prosper and Huckingen coke plants demonstrated that widening the ovens, to increase productivity and optimize profitability, had met all expectations in terms of operational advantages and, also, coke quality. The specified output was exceeded and ease of operation has been considerably greater than expected. The wider ovens reduced, appreciably, the length of sealing faces to be serviced and kept tight every day - from 7.2 to 5.3 km/day.

Increasing the oven chamber width led to an increase in the oven bulk density of the coal, to as high as 900 kg/m^3 (10% H_2O). This effect, in conjunction with the lower mean coking rate inherent with wide coking chambers, led to the unexpected result that poorly coking coals, which could not be added to the blend charged to standard, narrow-chamber ovens without the application of auxiliary techniques, can be carbonized in wide-chamber coke ovens with no problem. In fact, the Prosper plant is operated on a coal charge blend that contains no more than about 42 percent coking coals. The remainder of this blend comprises approximately 37 percent steam coals, 18 percent gas flame coal, and 3 percent pulverized coke breeze.

In summary, compared to the technology level reached prior to the realization of these projects, the wider ovens provide the following benefits[34]:

- productivity is increased by approximately 50 percent,
- the number of ovens pushed/day is decreased by approximately 33 percent,
- the length of sealing faces to be cleaned daily at doors and charging holes is decreased by approximately 25 percent from 7.2 to 5.3 km, and
- the range of coals which can be charged is increased to include high proportions of very low or very high volatile coals without additional stamping or preheating.

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* TAL: Technische Auleitung zur Reinhaltung der Luft

Ruhrkohle is continuing to pursue this path. A completely new coke plant to replace two old coke plants in the Dortmund area, Hansa and Kaiserstuhl II, is being constructed - the Kaiserstuhl III coke plant, located close to the old Kaiserstuhl II plant. The basic data for the new plant are the following:

- capacity: two million tonnes/year
- chamber width: 620 mm (average), in view of the success with wider ovens at Huckingen and Prosper
- coking time: 25 hours, based on coking chamber width and a mean heating flue temperature of 1340°C
- oven cycles: 115 pushes/day
- oven volume: 78.9 m^3 effective volume, based on 48.7 t coke/charge (5600 t/day ÷ 115 (pushes/day), 880 kg/m^3 (wet) bulk density and 78 percent coke yield
- oven length: 18.8 m
- oven height: 7.18 m effective height; with 450 mm oven free space, total height is 7.63 m.

The cost of the Kaiserstuhl III coke plant, including the coke dry quenching facility, was estimated at DM 690 million in 1987 (US $383 million at 1.8 DM/US$).

By the end of 1992, when the 2nd International Cokemaking Congress is held in England, Kaiserstuhl III may be available for viewing.

Pertinent data for all three of the "new design", wide coke ovens built recently in the Federal Republic of Germany are shown in Table XIII.

Table XIII: Summary Description of Wider Coke Ovens[36]

Description		Coke Plant		
		Huckingen (MRW AG*)	Prosper (RAG*)	Kaiserstuhl III (RAG)
Oven length (hot)	m	18.0	16.6	18.8
Oven height (total, hot)	m	7.85	7.1	7.63
Oven width (hot)	mm	550	590	620
Effective oven volume (hot)	m^3	70	62.3	78.9
Bulk density (wet)	kg/m^3	856	880	880
Coke weight (dry)	t/oven	43	38	47.8
Coking time	hr	22.4	24.5	25.0
Mean heating flue temperature	°C	1340	1310	1340

* MRW AG = Mannesmannröhren-Werke AG
RAG = Ruhrkohle AG

These projects represent significant improvements in cokemaking technology. However, the recognition was there that even more improvements in the technology were needed, which led to the concept of the jumbo coking reactor (next section).

Ruhrkohle is speculating on a new design for the total control of emissions from standard coke ovens. They perceive totally enclosing the coke ovens themselves in three separate halls; one hall to enclose the pusher side, one the top and one the coke side. These halls would collect all the emissions. The most contaminated air would be used for combustion of the flues. The larry car would be suspended from the roof. Actually, the larry car function would be split between two units; one would be a lightweight cleaning and lid preparation car which would run along the top of the battery and the other would be the larry car itself which would be suspended from the roof to take the weight off the

top of the battery and allow more freedom in top construction. The operating cost is estimated to be about one DM/tonne coke more than without the total controlled emission system.

Two future developments which are also under study are:

i) a 2-product coke plant in which only coke and hydrogen are produced, and

ii) a waste-water-free coke plant.

Details are not available, but these developments bear monitoring.

JUMBO COKING REACTOR

Ruhrkohle, in close association with Bergbauforschung, seems to be the only company looking at the next generation of coke ovens. They have discounted formed coke because the structure of the coke produced in coke ovens is much more suitable to the needs of the blast furnace. They carried out a systematic, engineering-related analysis of contemporary carbonization systems to develop a concept for an advanced new system, which resulted in the following criteria it would have to meet:

- independence from coal type,
- minimal number of coking reactors for a specific output,
- use of single, independently operated, process-controlled, coking reactors,
- minimized energy consumption, possibly by operation of a coke dry quenching plant in combination with coal predrying and/or preheating,
- resolution of problems of industrial hygiene, workplace safety, and environmental protection by adopting methods which ensure the prevention of causes rather than elimination of damage, and
- production of by-products either by traditional methods or by conversion, partly or wholly, into hydrogen and/or synthesis gas.

Thus was born the concept of the jumbo coking reactor.

The jumbo coking reactor is so designed that each reactor can be operated as an independent coking unit. Coking pressures possibly occurring during the carbonization of preheated coals will be transferred through thin runners and headers to be absorbed by laterally arranged vertical support walls, which means that the runners will serve primarily for heat transfer. Thus, the width of the heating flue will be guided merely by flow and combustion requirements to achieve an optimal heat supply. Design need not consider stability aspects; all forces and moments evolving will be absorbed by "rigid" partition walls. The function of the oven decking structure will be limited to a mere insulation function, because preheated coal will be charged into the reactors through closed, stationary systems. The rigidly arranged walls, it is believed by the proponents of this technology, will make it possible to dispense with the oven taper, even if poorly shrinking coals are charged. The lack of the traditional taper will provide advantages for oven construction and heating control. Transverse forces which might occur on coke pushing can be absorbed by heating walls and deflected to rigid partition walls. Several reactors can, and probably would, be grouped into blocks, but they will be so designed that they do not affect one another. Thus, they will be able to be repaired or retrofitted, if required, independently of each other.

The coke will be pushed by a conventional pusher machine "crash-free" into a closed cassette, a practice that is being developed by the Kress Corporation in the USA.[37-40] Subsequently, the cassette will be transported to the coke dry quenching facility and discharged there.

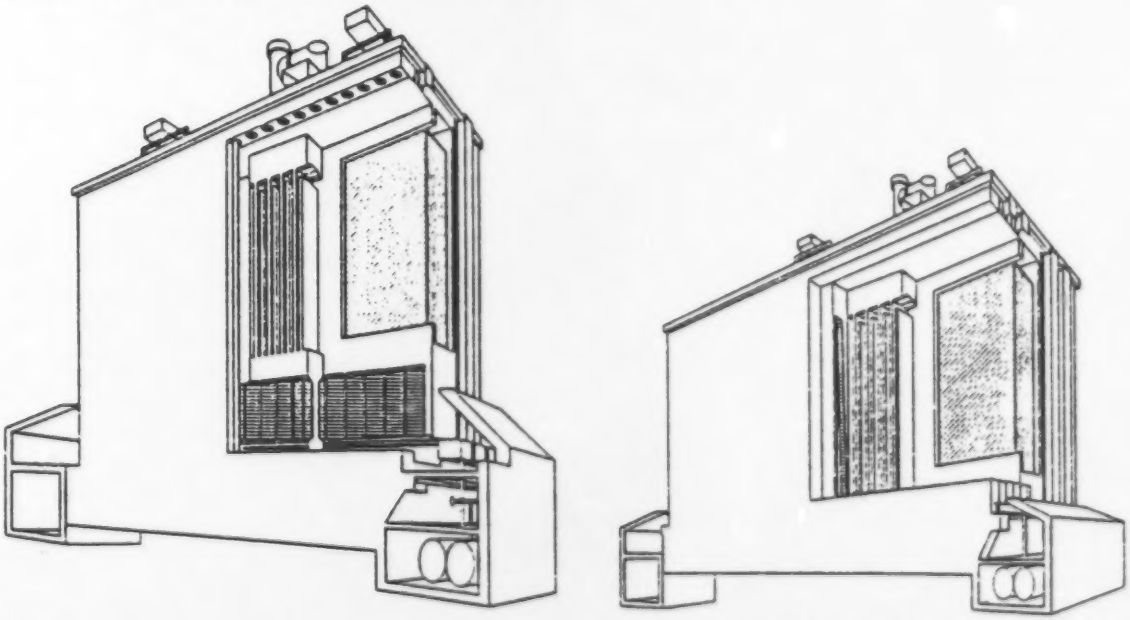
The doors of the jumbo coking reactor will be of the "ante-chamber" design type and supplied with inert gas serving as a barrier to prevent emission and condensate leakages.

Considering a productivity of 100 tonnes coke/reactor, the use of preheated coals carbonized in 24 hours operating time (permitting a two-shift operation), the coking chamber dimensions would be; height - 10 m, length - 19 m, width - 850 mm, and useful volume 150 m^3. However, the engineering study of the jumbo coking reactor has revealed that the productivity can be increased easily to 150 tonnes coke/reactor. Thus, the number of coking units required to yield two million tonnes of coke/year can be reduced from 123 (Ohgishima) and 120 (Kaiserstuhl III), to 55 (basic study, jumbo coking reactor), to 33 (engineering feasibility study). The productivity of coking units, therefore, will be increased from 32 tonnes coke/oven (Ohgishima), through 49 t/oven (Kaiserstuhl III), to 160 tonnes of coke/oven and more (engineering study). The 160 t ovens would have the following dimensions: 25 m long x 12 m high x 850 mm wide.

The operation of only 33 single reactors imparts tremendous advantages for environmental protection. The length of sealing faces which must be serviced and kept tight every day will be reduced substantially by another 70 percent to 1.8 km compared to the wide oven design. Thus, the prerequisites have been created for applying more sophisticated techniques to contain emissions at these areas, in the sense of prevention rather than cleanup.

For the construction of the jumbo coking reactor, two basic designs have been worked out, depending on the location of the regenerators - whether they are built beneath the reactor or alongside it - Figure 26.

Figure 26: Jumbo Coking Reactor - Two Designs[34]



a) Regenerators underneath

b) Regenerators alongside

With the proposed two-shift operation, coke oven gas production and composition will swing. A gas holder will be required to even out gas flow and composition.

The jumbo coking reactors will be heated with lean, low-calorific, blast furnace gas, of about 700 Kcal/Nm^3; this will be their standard design. In a situation where blast furnace gas is not available, they would dilute coke oven gas with flue gas to achieve 700 Kcal/Nm^3. Such lean gas is needed for flame length and, in addition, it creates less NO_x. The coking chambers would be lined with 60 mm of high thermal conductivity silica.

The combining of a coke dry quench system and the jumbo coking reactors has advantages in energy recovery and utilization. The heat recovered from the CDQ can be used to preheat the coal. Any excess would be used to produce process steam.

Preheating would be to <180°C. The hot coal would be charged by chain conveyor down a telescoping charging device. The filling of a coking chamber is expected to take about five minutes. No emissions will be released during charging; the gases created during charging will be sucked off into the adjacent reactor or to the (traditional) standpipes. Current plans call for charging by weight, but a detector is being developed to stop the chain conveyor when the coal reaches the correct height in the chamber.

Provided the jumbo coking reactor is a success, its implementation is anticipated to effect the changes in coke production costs noted in Table XIV.

Table XIV: Jumbo Coking Reactor: Production Cost Changes[34]

Cost Element Changed	Degree of Changes in Cost %
Coal (through decreased percentage of coking coal)	-10 to -15
Labor (a) 3-shift operation	-10 to -15
(b) 2-shift operation	-25 to -30
Energy	-25 to -35
Environmental protection, industrial hygiene, and work safety	-40 to -60
Specific capital investment costs (depending on basis of comparison)	0 to +10

The sum total of all of these cost effects is expected to add up to a decrease of up to 20 percent in the cost of producing coke.

Relative capital investment cost was provided as follows:

2 batteries x 64 ovens/battery, wet charge = index 100
55 reactors charged with preheated coal = index 103
33 reactors charged with preheated coal = index 98

The coal preheating facilities are probably not included in this index.

The first commercial prototype of the jumbo coking reactor plant is expected to contain 55 reactors and produce about two million tonnes coke/year. The pilot jumbo coking reactor will be one-half scale (length only), compared to the first prototype, i.e. 10 m long x 9.5 m high x 850 mm wide. Two of these pilot-scale reactors will be built, one of each design, i.e. regenerators underneath and regenerators alongside.

The pilot-scale reactors will be built at the Prosper coke plant of Ruhrkohle and the coke they produce will enter the coke stream of that plant. The total project will cost about DM 60 million (~US $33.3 million).

The next steps are the following:[41]

- 1989-90: complete the second engineering study,

- summer 1990: approval of project,
- 1990 (third quarter) to 1992 (first quarter): award contract, detailed engineering, construction,
- 1992 to 1995: gain experience with both designs of jumbo coking reactor,
- 1995: design for bottom regenerator reactor available for industrial adoption,
- 1996: design for side regenerator reactor available for industrial adoption,
- build a multi-reactor plant as a replacement for a coke oven battery that needs to be taken down.

This project has been approved for the Eureka program[41], the ECSC's program for the development of technologies required in the future. Besides ECSC funding, Ruhrkohle was also looking for paying partners in this project, with 100 shares being available at DM 600 000 each (~US $333 300 each at DM 1.8/US$). They were certain they would be successful and, in fact, at the time of our visit, Voest-Alpine had purchased two shares and discussions were ongoing with other companies. With ECSC funding, the partnership was limited to those in EEC countries. We noted mixed reaction to joining this project at the various places we visited.

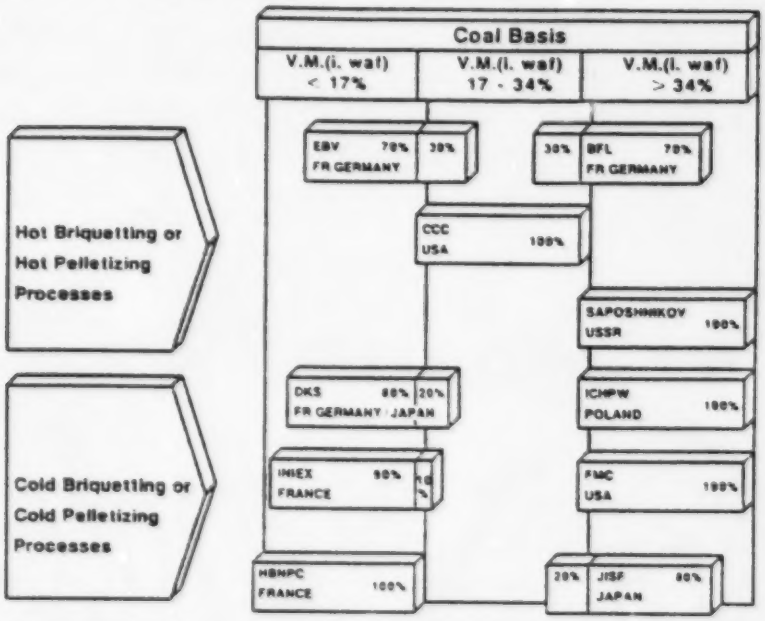
Ruhrkohle plan to license the process when they have proved it. The fee has not been definitely set but would be a single-payment lump sum based on the capacity of the coke plant, e.g. on a two million tonnes a year plant, the license fee would likely be DM 20 to 30 million (US $11 to $16.7 million). All shareholders are to share the income from license fees, based on the number of shares they hold.

FORMED COKE

Many formed coke processes have been developed in numerous countries over the years, virtually all of them for the same reasons - to produce coke for the blast furnace with a lower capital expenditure than for conventional coke ovens, for greater ease of pollution control than with conventional coke ovens, and to enable the use of lower-cost noncoking coals. Some of them reached the relatively large pilot plant stage and produced sufficient quantities of formed coke that it could be, and was, tested in a production blast furnace. However, none of them survived to commercial reality*; the only recent formed coke development activity of any note in the industrialized world has been in Japan.

Figure 27 summarizes many of these processes according to the type of coal they utilize and their basic forming method.

Figure 27: Summary of Formed Coke Processes[43]


Coal Basis
V.M.(i. waf) < 17%
V.M.(i. waf) 17 - 34%
V.M.(i. waf) > 34%
Hot Briquetting or Hot Pelletizing Processes
Cold Briquetting or Cold Pelletizing Processes
EBV 70% 30% FR GERMANY
30% BFL 70% FR GERMANY
CCC 100% USA
SAPOSHNIKOV 100% USSR
DKS 80% 20% FR GERMANY / JAPAN
ICMPW 100% POLAND
INIEX 90% FRANCE
FMC 100% USA
HBNPC 100% FRANCE
20% JISF 80% JAPAN

JISF Formed Coke Process[43-46]

Nippon Steel Corporation had been developing their own very promising formed coke process since the early 1970s. In 1978, under the sponsorship of the Japan Iron and Steel Federation, Nippon Steel Corporation was joined by Kawasaki Steel Corporation, Kobe Steel Limited, and Nippon Kokan KK, to take this process to the pilot plant stage, essentially as a national initiative. Nippon Steel Corporation was chiefly responsible for tests on the pilot plant which was built at its Yawata Works.

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* The one exception is the Ancit[42] formed coke process (Volume II), in a small plant at Alsdorf, near Aachen (~1.5 million tonnes of formed coke was produced from 1967 to 1987). While the Ancit formed coke was tested on a blast furnace, it is produced primarily as a solid, smokeless, environmentally harmless, domestic fuel.

The development work on this process proceeded as follows:

- 1981, May - construction of 200 t/day pilot plant started,
- 1983, December - construction of pilot plant completed,
- 1984, January - adjusting equipment, drying carbonizer, training operators, etc,
- 1984, June - hot testing began, and lasted through various stages until December, 1986; total operating time was 579 days and total production of formed coke was 93 000 tonnes of which 61 000 tonnes were set aside for testing in the blast furnace,
- 1984, December - completed optimization of operating procedures and improvements to some of the plant facilities,
- 1985, March - pilot plant ran for 30 days with no problems,
- 1985, May to 1986, July - formed coke was produced for stockpiling for a blast furnace test,
- 1986, August - testing of formed coke in Yawata No. 4 Blast Furnace (4250 m^3 inner volume) started,
- 1986, October through December - pilot plant operation under widely varied operating and coal blending conditions to achieve further improvement of the process, and
- 1987, January - blast furnace testing ended.

The end of the blast furnace testing of the formed coke undoubtedly was followed by a major period of data analysis and economic analysis.

Process Description

The process comprises several steps, such as coal preparation, briquetting, carbonization of briquettes, and gas cooling. In the briquetting process, coal is dried in advance and soft pitch is used as the binder. The kneading process in which the coal is mixed with the binder is a batch step; all the other steps are continuous. The briquetting process is conventional. The cold briquettes are carbonized continuously in the shaft furnace using gas as the heating medium. The formed coke process, as exemplified by the 200 t/day pilot plant, is shown in Figure 28.

The carbonizing process is the key element in the development of the process. Consequently, in the pilot plant it was provided with a number of innovative features. Its basic principle is that cold briquettes are carbonized continuously in a shaft furnace by controlling their carbonizing behavior according to the optimum heating pattern. The carbonizing temperature pattern based on this principle is shown schematically in Figure 29.

Figure 28: Process Flowsheet - 200 t/d Pilot Plant[43]

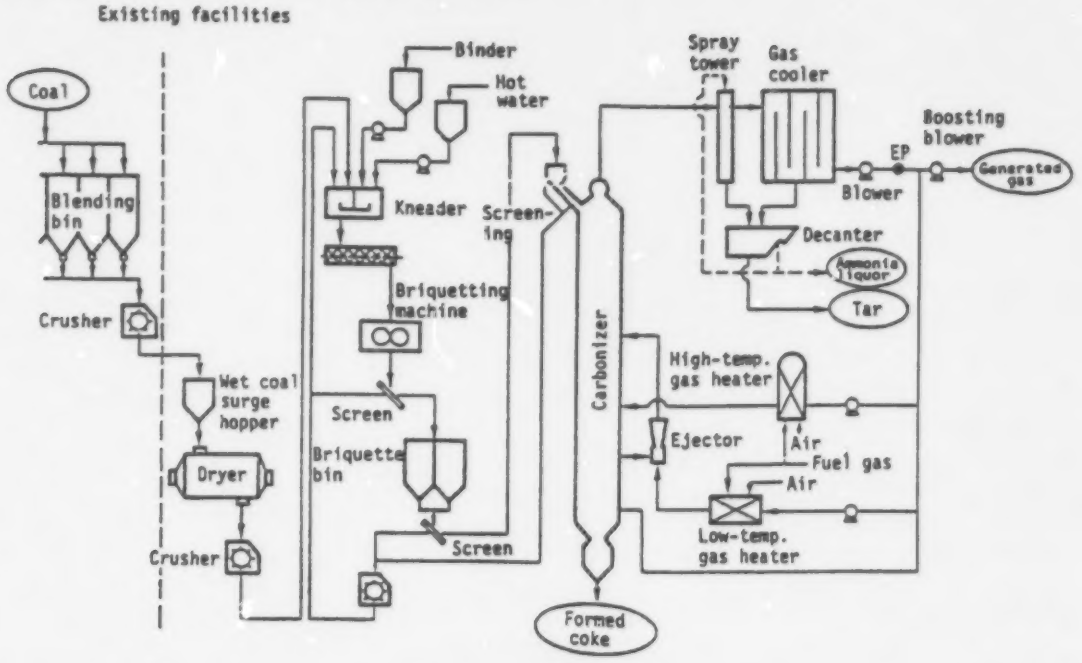
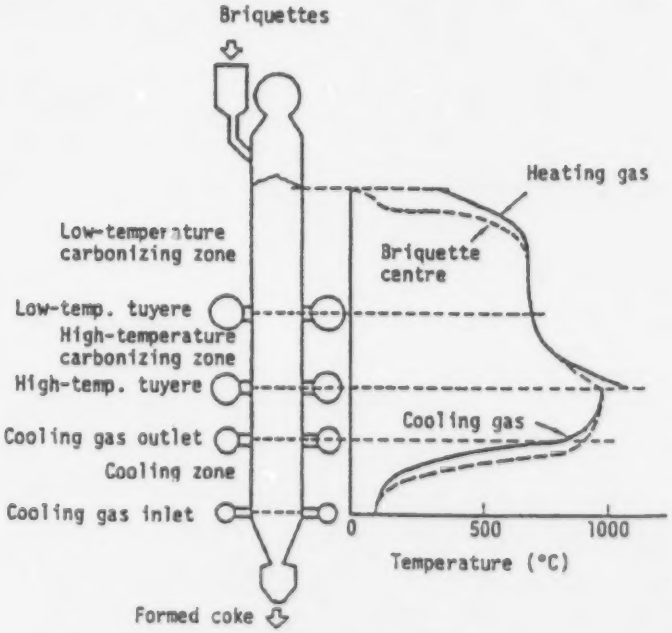


Figure 29: Carbonizing Temperature Pattern[43]



The four major innovations in this process are:

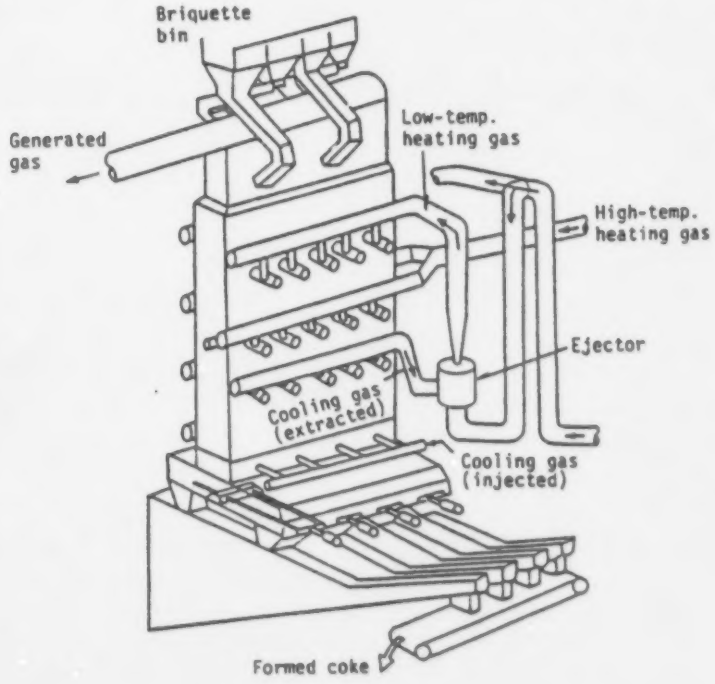
- briquettes are heated by regulating the heating rate via two rows of tuyeres so as to prevent their collapsing, bonding, swelling, cracking, etc,
- all operations, from carbonization to cooling, are carried out in the same carbonizer, so as to minimize the number of carbonizers,
- to recover high-calorific gas, the generated gas is preheated indirectly and recirculated as a heating gas, and
- to utilize the sensible heat of the coke for heating the briquettes, the gas used for cooling is extracted from the carbonizer and recirculated to the low-temperature tuyeres.

The pilot plant made good use of its location in Yawata Works; the coals were blended and crushed by the coke plant facilities and were carried to the pilot plant by conveyor belt. The recovered gas was piped to the generated gas main of the Yawata plant where it was mixed with the gas normally generated at Yawata and fed into the gas refining process.

The Carbonizer

The carbonizer is shown schematically in Figure 30.

Figure 30: Schematic Representation of Carbonizer[43]



The carbonizer had a rectangular cross section. To eliminate the problems which could arise in scaling up the carbonizer, the pilot plant carbonizer had the same width and height as those of commercial carbonizers; only its length was smaller.

The carbonizer had four charging devices along its length. Five tuyeres were installed along each header pipe for injecting the heating and cooling gases into the carbonizer and for extracting the cooling gas from it. An ejector was provided on each side of the carbonizer to extract and circulate the gas used for cooling the formed coke. The low-temperature heating gas was heated indirectly by a recuperator, while the high-temperature heating gas was preheated by hot stoves. Hydrocarbons contained in the circulating gas caused carbon deposits as they decomposed thermally inside the hot stoves; however, the gas circulating system burned away the carbon deposits with air during the switching of the hot stoves.

Blast Furnace Test

The objective of the test was to evaluate the possibility of using formed coke in a large blast furnace on a long-term basis. The features of the formed coke expected to influence blast furnace performance may be compared to the same features of conventional coke in Table XV.

Table XV: Features of Formed Coke and their Anticipated Effect[46]

	Conventional coke	Formed coke	[Effect expected at the time of uniform charging]	[Counter-measure]
Average size (mm)	48.9	38.0		
Void ratio (-)	0.50	0.44	Increase in permeability resistance	Charging of formed coke in periphery of furnace
Bulk density (T/m^3)	0.50	0.65		
Angle of repose (°)	42	38	Unstable burden distribution	
CRI (%)	29.2	36.6	Inactivation at furnace centre	

To counteract the possible negative effect that the formed coke might have on the blast furnace performance, Nippon Steel Corporation opted to peripherally charge the formed coke for testing. The blast furnace was operated continuously for 74 days with formed coke comprising 20 percent of the coke charge (30 percent for several days). During this time, the blast furnace's operational characteristics, such as fuel rate, solution loss, and burden descent, remained the same as when only conventional coke was used. However, the permeability resistance increased slightly because of the smaller size of the formed coke.

Coke samples collected at the tuyeres revealed the following:

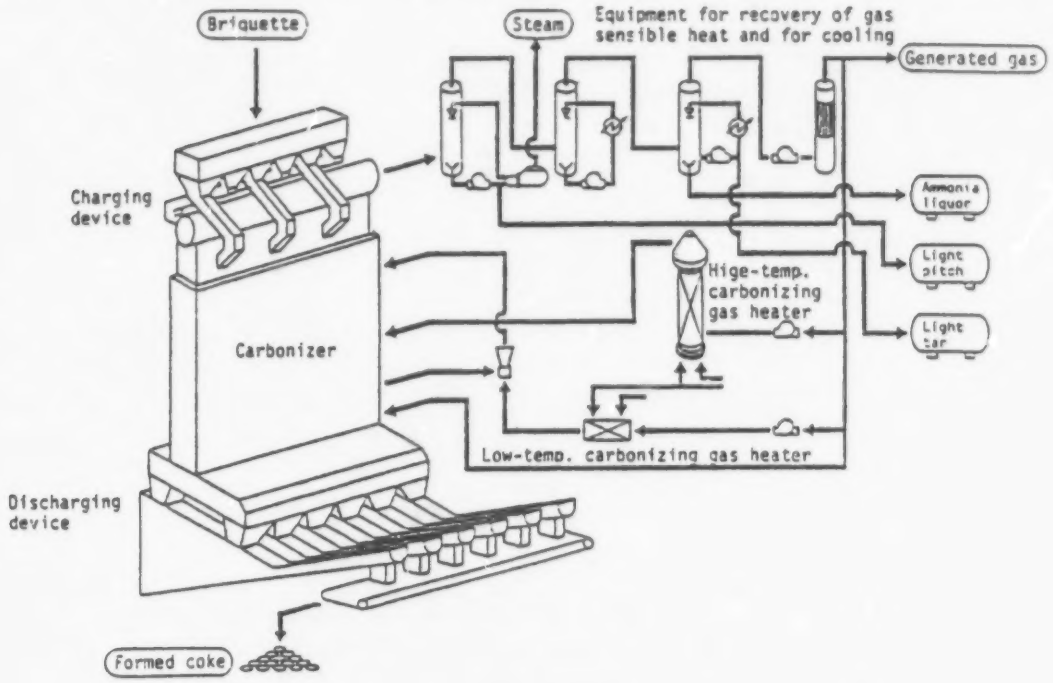
- the change (decrease) in lump size of the formed coke was the same as that experienced by conventional coke, and
- the formed coke retained its original shape to tuyere level at least.

The blast furnace test in Yawata's No. 4 furnace proves that formed coke produced by this process can be substituted for conventional coke, at least up to the 20 percent level.

Economic Considerations

The feasibility study by Nippon Steel Corporation, upon completion of the pilot plant work, was based on a formed coke plant having a production capacity of 3000 t/day and essentially the same flowsheet as the pilot plant. For the carbonizing process, however, a method to recover sensible heat from the top gas was incorporated, as shown in Figure 31, and the carbonizer length was three times that of the carbonizer of the pilot plant (the height and width remaining unchanged).

Figure 31: Flowsheet of Formed Coke Carbonizing Process[46]



Carbonizer operating conditions, productivity, product yield, etc. and, hence, the economics of the process, are influenced by the properties of the coal used as the raw material. Nippon Steel Corporation, therefore, considered three situations of formed coking, based on three types of coal blend, and compared them to conventional coke oven operation alone and with briquetting of a portion of the charge. The three formed coke cases are described in Table XVI.

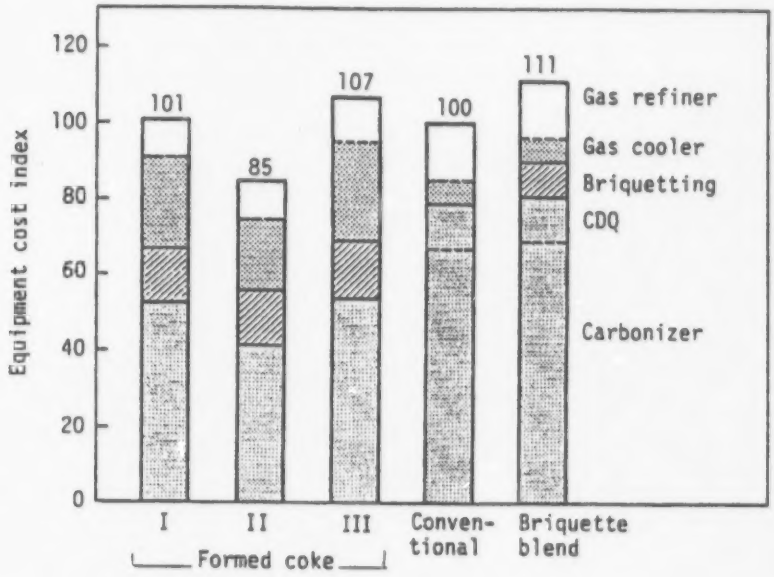
Table XVI: Economic Study - Formed Coke Cases[46]

Case		Properties of Blended Coal		Gas Temperature (°C)		Production Rate (%)
		VM (%)	CI	Top Gas	Low Temperature Tuyere	
I	Low VM - High CI	20 - 23	60 - 70	350	610	120
II	Low VM - Low CI	20 - 23	45 - 50	270	630	150
III	High VM - High CI	30 - 33	60 - 70	350	610	120

VM = volatile matter CI = coking index

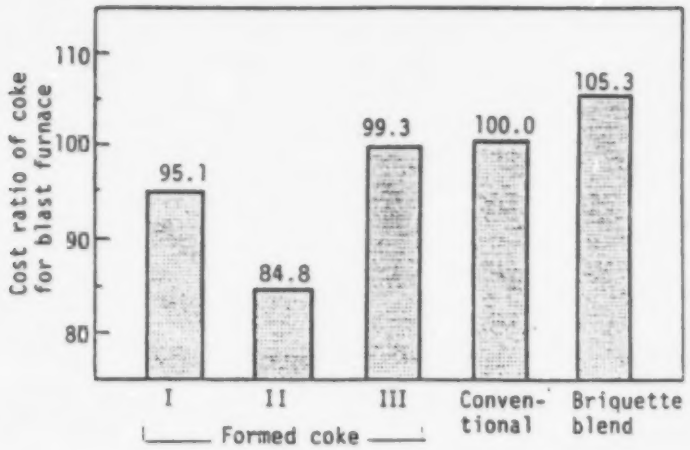
Nippon Steel Corporation's comparison of equipment costs is given in Figure 32, using a cost index in which the cost of conventional coke ovens is taken as 100. Case I is the same as the conventional process, Case II is less costly by about 15 percent, and Case III is more costly, but less costly than the briquetted blend coking process.

Figure 32: Cost Comparison of 3000 t/d Equipment[46]



The cost of blast furnace coke is compared in Figure 33, based on the current price difference between coking coals and slightly coking and noncoking coals.

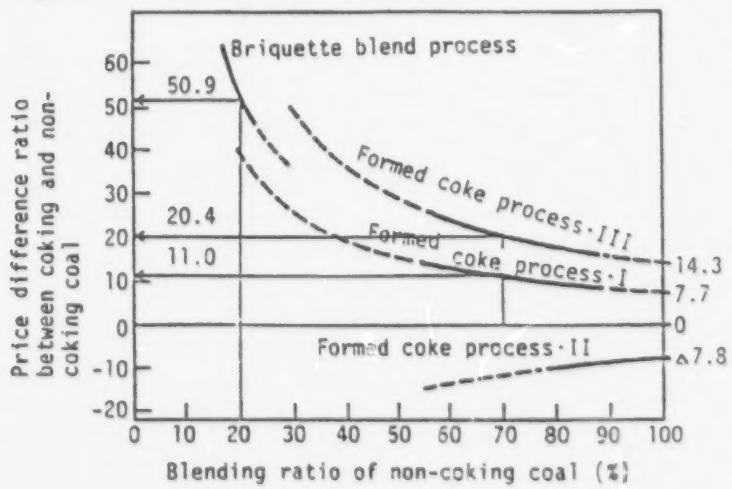
Figure 33: Comparison of Cost of Blast Furnace Coke[46]



The formed coke cases seem generally to be more advantageous than the conventional coking process in terms of cost of blast furnace coke, with Case II, in particular, being 15 percent less costly than conventionally produced coke. Briquetted blend coking is more costly than conventional coking.

By and large, the economic advantage of the formed coke process over the conventional coking process depends on the price difference between coking coals and noncoking to slightly coking coals. Figure 34 shows the results of Nippon Steel Corporation's evaluation of the economic advantage of the formed coke process over the conventional process, based on the cost differential alluded to above.

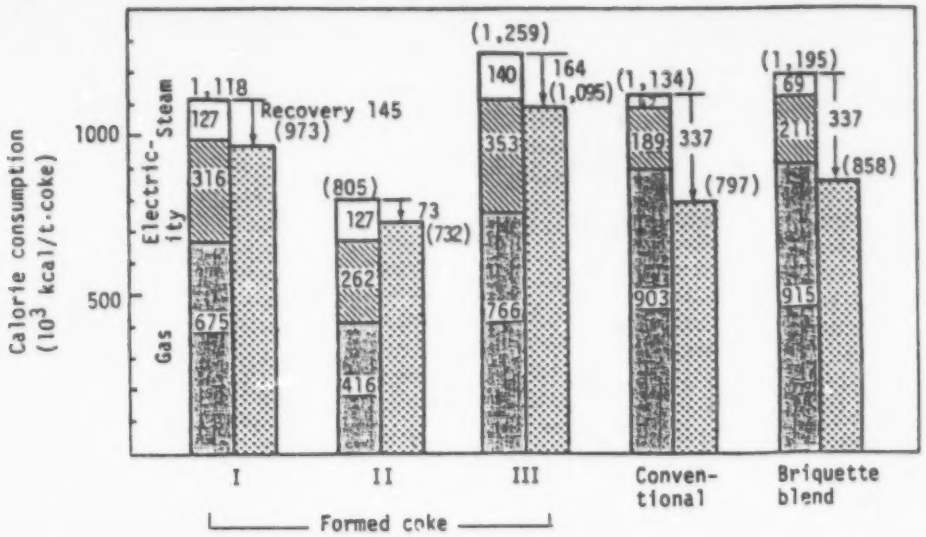
Figure 34: Economic Picture for Formed Coke[46]



The example shown in Figure 34 is for a coal blend feed to the formed coke process containing 70 percent noncoking or slightly coking coals. For Case I, the formed coke process becomes more economical than the conventional coking process when the coal cost differential exceeds 11 percent; Case III needs the cost differential to exceed 20 percent before it becomes the more economical process. Case II is always more economical than the conventional coking process even when there is no coal cost differential.

Nippon Steel Corporation also compared the energy requirements of the various cases and processes. Their comparison may be seen in Figure 35.

Figure 35: Comparison of Energy Requirements[46]



Cases I and III consume more energy than the conventional coking process. However, Case II, in which the temperature of the top gas can be lowered, consumes less. The formed coke process, compared to the conventional, is characterized by lower gas consumption, but higher electricity consumption.

Future[47]

The process has been developed, the product has been tested, the pilot plant has been shut down, and the capability to design and build a commercial JISF formed coke plant is in place. Environmentally the process is good; its main drawback according to our Japanese contacts, apart from its product's inferiority to conventional coke, was its high investment cost.

As far as we were able to ascertain, Nippon Steel Corporation has no plans to build a commercial plant based on this process, nor have most of the other Japanese steel companies. Kawasaki Steel Corporation, however, is still interested in this process. Because of the age of their coke ovens, they cannot wait 10 to 15 years for a new coking process to be developed. Kawasaki, therefore, is proceeding with a paper study of potential new coking processes to determine whether the JISF formed coke process could be improved quickly and brought into commercial production.

COAL IN STEELMAKING

The designation "coal in steelmaking" covers a wide range of processes. Broadly speaking, they can be divided according to the shape of the reaction vessel into BOF-based, electric arc furnace-based, and others. Table XVII is a compilation of the processes which have been studied and/or developed to use coal in steelmaking. (They are each described briefly in Volume II.)

Table XVII: Steelmaking Processes Using Coal

Process	Developer
BOF-Based:	
Arbed Lanced Coal Injection (ALCI)	- Arbed/Nippon Steel Corporation
Bath Agitation Process (BAP)	- British Steel Corporation
C-FFOX Process	- CIREP/Sollac
Klöckner/Voest-Alpine (KVA)	- Klöckner Stahl/Voest-Alpine
KMS/KS Process	- Klöckner Stahlforschung
New Melting Process	- Nippon Steel Corporation
Scrap Melting Method	- Sumitomo Metal Industries Limited
Tula Process	- Tulachermet (USSR)
EAF-Based:	
Klöckner-Electric Steel Process (K-ES)	- Klöckner CRA Technology Group
Other:	
Energy Optimizing Furnace (EOF)	- Korf Group/Korf's Brazilian Steel Mill, Compania Siderurgica Pains
Reactor Process	- Daido Steel Company, Limited

Most of the BOF-based processes were developed to increase the scrap charge to the BOF; however, when the price of scrap increases, the incentive to use these processes diminishes rapidly - since they do incur additional costs compared to the BOF and their productivity is invariably lower, all else being equal.

Some of them, the C-FFOX, KS, KVA, NSC's New Melting, and Tula processes, are capable of using a 100 percent scrap charge. With the possible exception of the Tula process, about which we have no current information, none of these processes was operating commercially at the end of 1989.

The status of these processes is shown in Table XVIII.

Table XVIII: Status of Steelmaking Processes Using Coal

Process	Status
ALCI	- Commercial (Belval Works, Arbed; and Kimitsu Works, NSC)
BAP	- Commercial (several plants, BSC)
C-FFOX	- Industrial tests
KVA	- Commercial (Voest-Alpine, but shut down for pollution reasons)
KMS/KS	- Commercial
New Melting Process	- To be implemented (Hirohata Works and Muroran Works, NSC)
Scrap Melting Method	- 10-tonne pilot plant (SMI)
Tula	- Tested cn converter
K-ES	- Commercial (Ferriere Nord SpA and Acciaierie Venete SpA)
EOF	- Commercial (Compania Siderurgica Pains and Compania Siderurgica Aliperti)
Daido Reactor	- Pilot scale tests

Of these 11 processes, those most likely to affect the Canadian situation are:

- the KMS/KS process, because of its commercialization,
- NSC's New Melting process, because it will affect coal purchases by NSC,
- the K-ES process, because it is directly applicable by the minimills, and
- the EOF process, because it has such wide potential applicability.

We shall consider each of these processes individually.

KMS/KS PROCESS

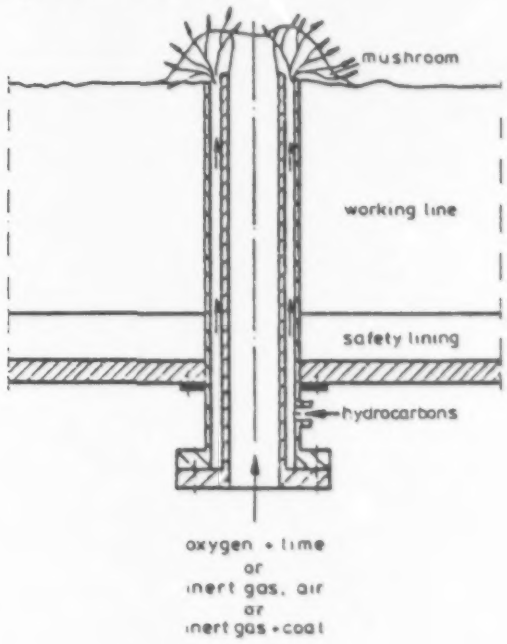
The KMS/KS process was developed by Klöckner Stahlforschung, West Germany. The objective was to increase the flexibility of using scrap in (BOF-type) steelmaking. The KMS process allows an optimum scrap feed of 35 to 65 percent, compared to 18 to 25 percent in a BOF; the KS process is an extension of the KMS process to 100 percent scrap.

Process Development

Most of the Klöckner family of steelmaking processes were pioneered at Klöckner's Maximilianshütte (Maxhütte) Works at Sulzbach Rosenberg, Bavaria. The development of the KMS/KS process was a progression of modifications to the BOF process to provide desired, defined advantages. This progression was in three major steps:

- 1968 - Since 1968, the OBM (Oxygen Blowing Maxhütte) process has been in industrial use at Maxhütte Works. In the OBM process (called Q-BOP in North America), oxygen and lime are blown into the vessel through the bottom, obviating the need for top blowing. The key to the success of the OBM process was the OBM tuyere developed and patented by KCT (Klöckner Contracting and Technology) - Figure 36.

Figure 36: OBM Tuyere[48]



A circumferential shroud of hydrocarbon (natural gas, oil or propane) is provided around the oxygen jet by the double pipe design. The endothermic cracking of the hydrocarbons at the tuyere tip produces a local cooling action and forms a protection around the annulus often referred to as a "mushroom". This tuyere is also the key to the success of the next two steps in the development.

- 1977 - The K-OBM (K = kombiniert, i.e. combined) process was developed out of the OBM process. It combines oxygen bottom-blowing and lime powder injection with partial (~30 percent) top-blowing. Oxygen is top-blown either through a movable post-combustion lance or through side tuyeres installed in the upper cone. Its main purpose is the post-combustion of the carbon monoxide exiting the bath to improve the heat balance and, also, to increase the scrap-melting capacity of the process.

- 1978 - The injection of fine-grained coal in large quantities was demonstrated, offering the possibility of greatly increasing the scrap charge - essentially, the KMS process was born.

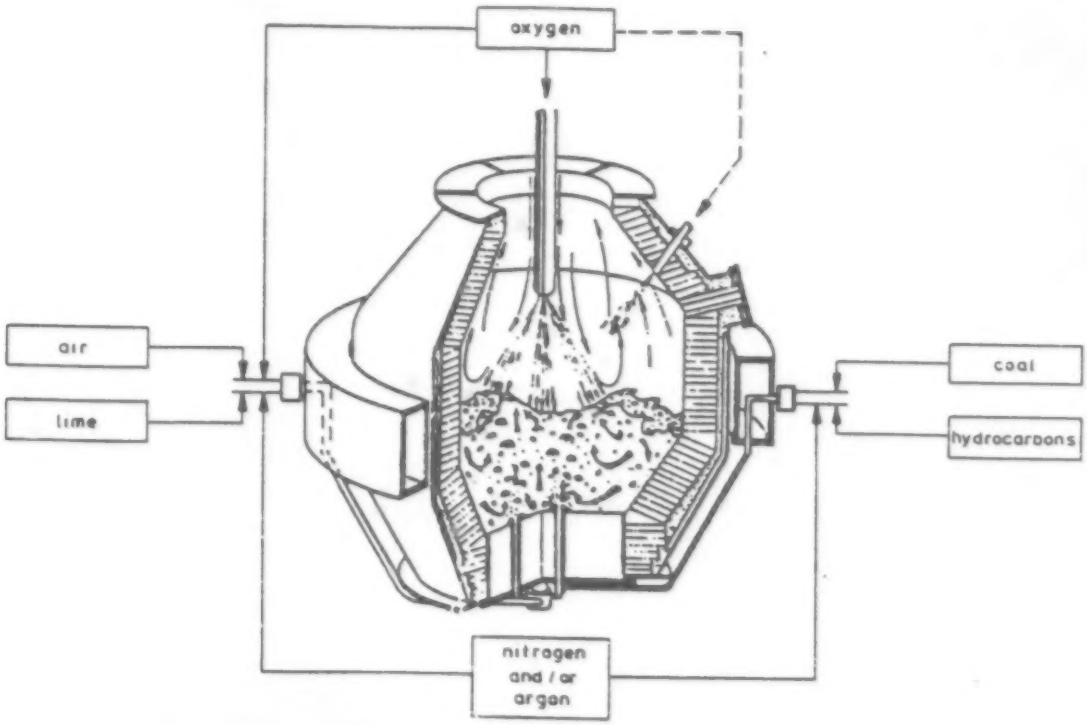
- 1981 - The KMS process began operating at the Georgsmarienhütte (GMH) Works of Klöckner-Stahl GmbH. Since, 1981, both the KMS process and the KS process (KMS with 100 percent scrap) have been used extensively at this plant.

- Further developments in the KMS process include:
  - recovery of the converter off-gas for use as an in-plant fuel, and
  - injection of converter dust from the off-gas dedusting system (up to 70 percent of the dust make) back into the converter.[49]

Process Description

The KMS process is shown diagrammatically in Figure 37.

Figure 37: Diagram of KMS Process[48]



In addition to the energy contained in the hot metal, the energy sources of the KMS process are scrap preheating, post-combustion, and the addition of carbon carriers.

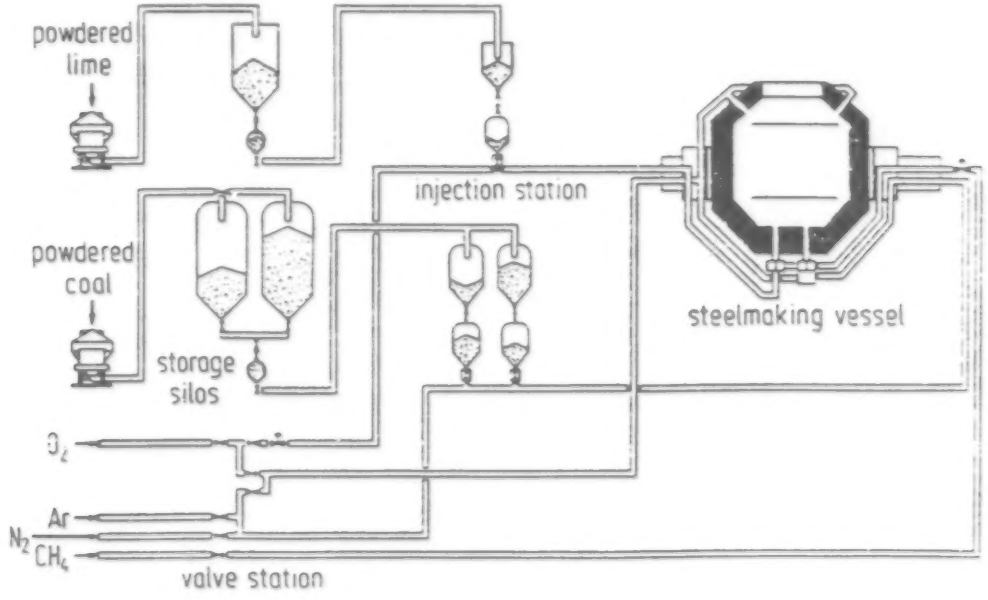
Scrap preheating utilizes both top and bottom injection ports and is carried out in such a way that local hot spots are avoided and scrap oxidation is kept to a low level. A precondition for this technique is the OBM bottom tuyeres, in this case used as burners. Since heat transfer from the hot gases to the cold scrap is high, much of the energy needed for scrap melting is absorbed during preheating. Preheating cuts the coal consumption in the KMS process by about 25 percent, corresponding to a scrap rate increase of about 75 kg/tonne of liquid steel.

The usual mode of KMS operation at high scrap rates entails two scrap charges because a large scrap load can freeze all the hot metal added and, therefore, the liquid heel necessary for coal injection would then be absent. However, preheating transfers enough heat to the scrap that a liquid heel is always present when hot metal is added, permitting the scrap to be single-charged.

Post-combustion is of the utmost importance to the addition of carbon carriers; it has a decisive influence on the energy yield in the converter and, thus, determines the quantity of coal or coke required. According to KCT, an optimum relationship exists among lance height, the type of lance tip, the amount of bottom oxygen, and total post-combustion. However, this information is proprietary and no details were provided.

The subsurface injection of large amounts of coal or coke directly into the metal bath requires special injection techniques and operationally safe injection hardware. The flowsheet for the KMS injection plant at Georgsmarienhütte is shown in Figure 38.

Figure 38: The KMS Plant at Georgsmarienhütte[48]



The KMS process can adjust the energy balance in the bath by varying the amount of coal injection to meet the economically optimum ratio of hot metal and scrap, restoring the flexibility of raw materials selection in steelmaking which was reduced when the steel industry switched from the open hearth process to the BOF.

In Europe, the preferred coal is lignite char, 1.0 to 2.0 mm, and, to a lesser extent, anthracite, <1.0 mm. The lignite char is preferred because it has a basic ash. It contains about 3.5 percent volatile matter, 8 percent ash, and 0.35 percent sulfur. KCT has studied the potential to use petroleum coke in the Venezuelan or Argentinean context, but no further information was forthcoming.

The KS process can melt 100 percent solid material charges in a converter equipped for bottom coal/oxygen injection and top oxygen injection. It requires the right coal, char, or coke breeze.

A variant of KMS and KS metallurgy is a two-step steelmaking process. Step 1 is melting and carbonizing scrap by coal injection and post-combustion to make a pseudo or synthetic hot metal containing about four percent carbon, very low silicon, phosphorous and sulfur, and having a temperature of 1400° to 1500°C. Step 2 is refining this hot metal in a K-OBM, although a BOF with bottom stirring would be an alternative. This variant would probably utilize two ironmaking converters to feed one steelmaking converter.

Economic Considerations

The advantages of the KMS process[48] are:

- the most economical raw materials selection can be made on a heat-to-heat basis; scrap input variations from 35 to 65 percent can be accommodated,
- production slowdowns in the blast furnace can be compensated for by increasing the scrap content of the charge,
- steel output can be increased, if excess steelmaking capacity is available, without having to increase hot metal production,
- steel output can be maintained without having to replace older, less economic, blast furnaces as they are shut down and,
- it can use every iron charge material available on the market, i.e. all types of scrap, DRI, fragmented iron, HBI, solid pig iron and iron ores.

It is virtually impossible to give general capital costs with any accuracy since every plant is unique. An order of magnitude estimate, in 1985, to adapt a two-furnace 1.5 million tonnes/year BOF shop to KMS technology, including coal injection equipment, but not desulfurization or gas handling, was about US $34 million.[50] The best estimate of such costs, if the advantages look interesting for a given plant, would be obtained by having the vendor estimate what they would be specifically for that plant. KCT, having licensed KMS/KS technology to a number of plants, should be well able to provide reasonably accurate capital cost estimates.

Likewise, it is virtually impossible to give general operating costs with any accuracy because the economics are different for each plant and the process can be configured in several ways.

The cost of steel produced by the KMS/KS process, based solely on raw materials and excluding refractories and desulfurization costs, may be calculated for a specific plant from the data in Table XIX (data for the BOF are included for comparison).

Table XIX: Raw Material Requirements/Tonne Steel[50]

Raw Material		Process			
		BOF	KMS-40[1,5]	KMS-52[2,5]	KS[3,5]
hot metal	(kg)	862	626	479	-
cold iron	(kg)	31	31	31	31
scrap	(kg)	185	417	555	1029
ore	(kg)	1.7	1.7	1.7	1.7
burnt lime	(kg)	40.0	36.2	31.2	20
dolomitic lime	(kg)	11.6	11.6	11.6	11.6
fluorospar	(kg)	3.4	-	-	-
coal	(kg)	-	37.2	84.1	298
oxygen	Nm^3	490	694	1022	1280
natural gas	Nm^3	-	20	49	85
hot metal ratio	(%)	80	60	40	0
tap-to-tap time	(min)	50	58	70	110
heats/day[4]		26.4	22.8	18.9	12

[1] - nominal 40 percent scrap
[2] - nominal 52 percent scrap
[3] - estimated
[4] - 22-hour operating day
[5] - from Klöckner

The higher tap temperatures, required to accommodate the longer desulfurization times during ladle treatment, if no reheat facilities are available, and the lengthened refining times, because of the coal injection, will reduce vessel lining life, especially in the KS mode of operation.

Licensing Arrangements

Licensing arrangements for the KMS/KS process include a one-time lump sum payment based on the capacity of the equipment. This payment gives the licensee a technology package. If the licensee requires equipment, training, commissioning help, start-up assistance, etc, a technical assistance contract is available, but it is a separate package.

If the adoption of KMS/KS technology expands, KCT sees their main growth areas as being Europe, North America, and Japan. KCT is expecting little by way of new customers for their sophisticated converter processes; such processes have become increasingly difficult to sell over the past five years as more and more companies turned to ladle metallurgy. However, they do see an opportunity to sell all-converter processes, according to the Nippon Steel Corporation technology which is based, essentially, on the KS process.

According to KCT, NSC has purchased a license for the KS process for their New Melting all-converter process. Thus, NSC's work is important to KCT, and they would like to use the NSC plants as demonstration units to which they can refer potential clients. They see the NSC installations as being an answer to pollution problems of the coke ovens/sinter plant/blast furnace/BOF route to steelmaking. NSC's New Steelmaking process must use coke or anthracite, however.

KCT recognize an opportunity for the sale of the New Steelmaking process technology in Eastern European countries and, in fact, are negotiating with some companies. These countries apparently see the need to replace their open hearth furnaces very rapidly, and KCT looks on the NSC version of the KS process as a viable replacement technology.

KCT consider the Tula process as a KS process variation, with the KS being the superior process. Since the USSR is becoming open to the importation of KCT technologies, their belief is that the Tula process will disappear. R. D. Pelke[51] reported in 1989 that a 16 million tonnes/year steel plant, Magnitogorsk Works, was replacing part of its (open hearth) steelmaking capacity with a new two-vessel BOF shop which will use KMS technology. It will be able to handle 350-tonne heats, and will produce about five million tonnes of steel a year. A subsequent vessel, scheduled to be put into operation in 1995, will allow this shop to expand steel production to nine million tonnes a year.

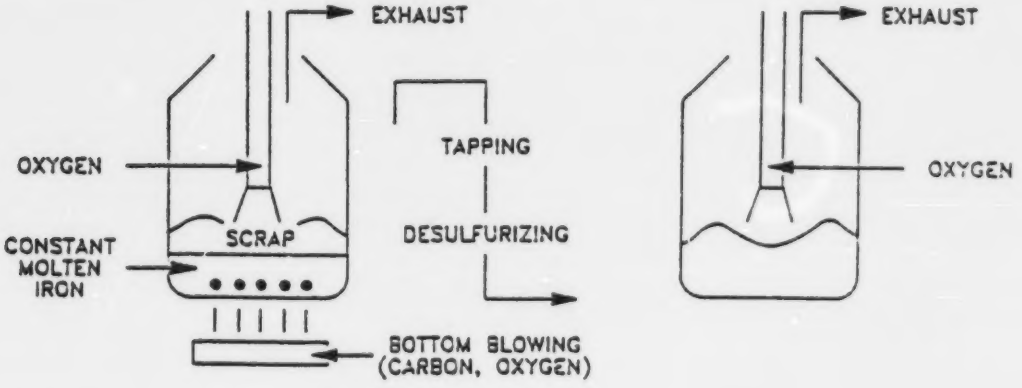
NSC's NEW MELTING PROCESS

No commercial installations of this process exist. However, it is of interest because NSC announced publicly that they will shut down two blast furnaces, No. 4 at Hirohata Works and No. 2 at Muroran Works, and replace them with this technology with essentially no decrease in steel production from the respective Works.

Very few details of this process are available from the literature and we were not permitted to visit the plants. Nor would our NSC hosts discuss the process. The process operates according to the diagram in Figure 39.

Figure 39: NSC's New Melting Process[52]

(a) Melting Furnace **(b) Decarburizing Furnace**



The process, as it is to be practiced by NSC, actually requires three BOF-type vessels to be converted:

- one to a melting furnace,
- one to a decarbonizing furnace, and
- one to a combination or swing furnace.

The melting furnace will operate as follows. The scrap and pig iron will be charged on top of a hot heel; coal and oxygen will be blown into the charge from the bottom and oxygen will be blown in from the top. When the melting operation has been completed and the hot metal has achieved the correct conditions, the hot metal is tapped, leaving a hot heel for the next heat. (Burners would be required to establish the molten pool for initial start-up).

The molten iron is desulfurized and charged into the decarbonizing furnace which seems to be, essentially, a top-blown BOF converter. The steel produced is reported to be of high quality, the same as that produced by the blast furnace/BOF route [probably more a function of high quality scrap than of the process].

The swing furnace allows for either of the other two furnaces to be taken out of service for reline, since it can be operated in either the ironmaking or steelmaking mode. At Hirohata Works, a 120-tonne converter will be remodelled into a melting furnace, another 120-tonne converter into a decarbonizing furnace, and a third 120-tonne converter into a combination furnace. This mill's capacity will be 47 000 tonnes a month.[53]

At Muroran Works, a 340-tonne converter will be remodelled into a melting furnace, a 150-tonne converter into a decarbonizing furnace, and a 340-tonne converter into a combination furnace. This mill will be capable of producing 82 000 tonnes a month using the New Melting process.[53]

The steel scrap and solid pig iron needed by the two mills for the New Melting process will be supplied from Kimitsu Works and Oita Works.

The investment cost for Nippon Steel to switch to the New Melting process at the two plants has not been officially released, but estimates place it between ¥6000 million and ¥7000 million[54] (US $40 to 47 million). Another estimate placed the cost at ¥8000 million[53] (US $61.5 million).

The advantages of the New Melting process are stated to be the following:

- existing BOF converters can be used, thereby saving capital,
- energy costs are decreased because the process uses steam coal, and
- production is flexible - the process can be stopped or restarted freely in response to business conditions.

Some of the information appears to be contradictory. On the one hand, two blast furnaces, producing in total about 9700 thm/day, are to be shut down, with essentially no decrease in the approximately 10 100 t steel/day that that hot metal would produce. On the other hand, the total steelmaking capacity of the two New Melting process units is 129 000 t/month, i.e. 4300 t steel/day

The remaining blast furnace at each plant may be able to produce additional hot metal to increase steel production in the BOF, but would not come close to maintaining steel production at the two plants close to 10 000 tonnes/day.

However, the tone of the published information suggests that Nippon Steel is expecting their New Melting process to replace the steelmaking capacity lost when the two blast furnaces are taken out of service. ("By introduction of the new process, Hirohata Works and Muroran Works will suffer only mild cuts in crude steel output and in workforce,...")[52] If this is the case, the effects are estimated as follows:

- decrease in coking coal required ..... >2 Mt/year
- decrease in injection coal required ..... >140 000 t/yr
- coal required for New Melting process ..... ~1.1 Mt/yr

The coal type has not been disclosed but, based on the KS process, low volatile coals are the most likely.

NSC's New Melting process bears a striking resemblance to Klöckner's KS process in which steel scrap is charged onto a hot heel of molten steel in a top and bottom-blown BOF converter. Coal and oxygen are bottom-blown during the melting phase; oxygen is top-blown during the melting phase and continues through the refining phase. The major difference seems to be that NSC uses two vessels, one for melting/carbonizing and one for refining, with desulfurization in between, while the KS process uses only a single vessel. While we were visiting Klöckner Contracting and Technology (KCT), we learned that Nippon Steel Corporation had recently (1988) taken out a license from KCT to practice KS process technology and KCT were hoping to be able to use the NSC plants as demonstration plants to promote KS technology.

NSC had scheduled the closure of the two blast furnaces and the introduction of the New Melting process at Hirohata and Muroran for 1989, but announced in October the postponement of these plans because of strong steel demands, primarily in construction. The closure of these blast furnaces has been rescheduled for March 1991.[55]

K-ES PROCESS

The K-ES (Klöckner-Electric Steel) process was developed by the Klöckner CRA Technology Group, in conjunction with Tokyo Steel Manufacturing Company, to decrease the electric power requirements of the electric arc furnace steelmaking process and to enable the recycling of EAF dust. The Klöckner Group provided the adaptation of the main principles of their OBM, K-OBM, and KMS converter technologies; Tokyo Steel provided a 27-tonne electric arc furnace, in which to develop the process, and the knowledge, experience, and interest of an electric arc steel producer respected worldwide. Those measures considered to be particularly important[56] included:

- the addition of pulverized and/or lump coal to increase the rate of energy input and to replace electrical energy by primary energy,
- the efficient combustion of the process gases in the furnace by multi-lance post-combustion, with the effective transfer of the heat to the scrap and to the melt, and
- the acceleration of the melting process through the above-mentioned addition of primary energy, through oxidation, and through increase in bath movement.

Process Development

To implement the joint development, one of the two 27-tonne EAFs at Tokyo Steel's Kochi Works was outfitted with the equipment required to develop the process. Development proceeded as follows:

- 1985 - Test work began at Tokyo Steel's Kochi Works and carried on for about 18 months. They studied coal injection at various locations, including through the bottom, through the side, and through the electrodes. They injected oxygen, nitrogen, air, and propane through submerged tuyeres and they studied post-combustion. A productivity increase of 20 percent and electrical energy savings of about 120 kWh/tonne, for power consumption of less than 300 kWh/tonne, demonstrated the potential of the process.

- 1988 - Ferriere Nord SpA, Osoppo, Italy, decided to install K-ES on its 80-tonne EAF.

- 1989 - The first K-ES heat was tapped at Osoppo in March.

- 1989 - Acciaierie Venete SpA, Padua, Italy, purchased a K-ES license. The first K-ES heat was tapped in this plant in December 1989.

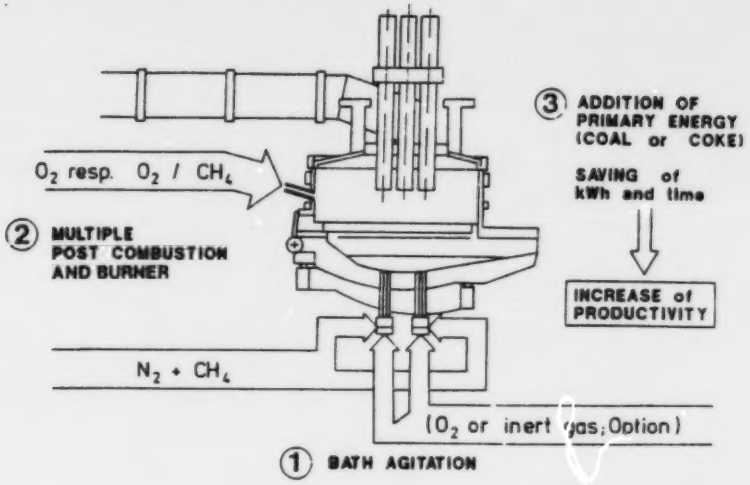
Process Description

The key elements of the K-ES process are the bath agitation through gas injection via submerged tuyeres, the addition of primary fuel (coal or coke), and additional process heat through the multi-lance post-combustion of the furnace gases.

The coal may be injected as fines or added as lump with the scrap charge. The coal addition rate decreases as the pig iron portion of the charge increases and vice-versa. Through the design of the lances and their correct location in the sidewall, an efficient transfer of the heat from post-combustion can be effected.

The key elements of the K-ES process are shown in Figure 40.

Figure 40: Elements of the K-ES Process[57]


3 ADDITION OF PRIMARY ENERGY (COAL or COKE)
SAVING of kWh and time
INCREASE of PRODUCTIVITY
O_2 resp. O_2 / CH_4
2 MULTIPLE POST COMBUSTION AND BURNER
N_2 + CH_4
(O_2 or inert gas; Option)
1 BATH AGITATION

The K-ES process incorporates dust recirculation; a dry off-gas dust collection system is required. The dust is injected as a blend with the coal. It is recirculated until its zinc content becomes high, e.g. 35 percent, at which point it is bled off and sold to a zinc producer.

The K-ES process is charged with regular EAF scrap. It can also be adapted to use direct reduced iron (DRI). Scrap preheating is a "must" with the K-ES process so as not to waste the rich carbon monoxide gas that it generates.

KCT had essentially standardized the K-ES process at the time of our visit, with the exception of finalizing the coal injection parameters - the best location to inject the coal, lump coal versus powdered coal, the best timing for the coal injection, post-combustion versus oxy-fuel burners, etc. Standardization of the K-ES process was expected to be completed by about March 1990. Even at that, the statement was made that post-combustion must be designed specifically for a given furnace.

Most of the modern EAFs have water-cooled panels. With post-combustion, as in the K-ES process, these water-cooled panels must be maintained much more rigorously than with no post-combustion.

With a rammed refractory bottom in the furnace, the area around the tuyeres eroded rapidly, and so high quality bricks were installed around them, solving this problem.

Without a "dog-house", the environmental problems are somewhat intensified compared to normal operation as an EAF. At the Venete installation, which does have a "dog-house" with secondary dedusting, operation in the K-ES mode was no different environmentally than operation in the normal EAF mode.

K-ES at Ferriere Nord SpA[57]

The EAF furnace adapted to K-ES was built in 1975. It is described in Table XX.

Table XX: K-ES Furnace at Ferriere Nord SpA

Parameter		Size
Shell diameter	(mm)	5300
Tap weight	(tonnes)	80
Transformer capacity	(MVA)	40
Maximum secondary voltage	(V)	533
Electrode diameter	(mm)	600
Features: - water-cooled walls and roof - coal injection unit - bottom tuyeres - post-combustion lances		

This furnace has no preheating, no bottom tapping, and no ladle furnace. It supplies steel to a 5-strand, 130 mm square, billet caster.

During the first K-ES campaigns, the consumption of refractory material was higher than during EAF operation. Also, problems were experienced with leaking sidewall panels. An optimization of the post-combustion lances/burners and their operation suppressed these problems.

Electrode consumption rate was initially higher with K-ES. However, by the end of 1989, the difference was down to 0.1 to 0.15 kg/tonne. They fully expect, with optimization of the process, that electrode consumption will decrease to its former level or lower.

The tuyere wear with gas bubbling amounted to about 0.35 mm/heat. As the K-ES shell is changed after 140 heats (one week of operation), total tuyere wear was 50 mm. The tuyeres can be exchanged easily, if necessary.

The behavior and influence of the slag show advantages for the K-ES process. The FeO content is about 25 to 30 percent lower than in the EAF process. Furthermore, through the capability of injecting coal at any stage during the melt, a foamy slag can be readily developed and controlled.

Nitrogen and hydrogen can be held to the necessary low levels through adjusting the type and flow rates of bottom gas in the various stages of the melt.

As of October 1989, they had installed OBM-type tuyeres and had run two campaigns with bottom oxygen blowing. The wear of the oxygen tuyeres was 0.3 to 0.8 mm a heat, i.e. it was less than tuyere wear in the converter processes. Their plans were to increase the bottom oxygen flow rates.

K-ES operating results, reported in March 1990, are shown in Table XXI along with the prior performance of the EAF.

Table XXI: K-ES Operating Results[58]

Parameter		K-ES		EAF
		3 Bask[1]	2 Bask[1]	
Tap-to-tap time	(min)	55	50	60 to 70
Power-on time	(min)	44	40	-
Tapping temperature	(°C)	1685	1685	-
Electricity consumption[2]	(kWh/tgb[3])	330	320	<400
Oxygen consumption	(Nm^3/tgb)	50 to 55	50 to 55	30 to 40
Natural gas consumption	(Nm^3/tgb)	6	6	-
Coke/coal consumption	(kg/tgb)	23 to 14	23 to 14	-
Pig iron in charge	(%)	10 to 30	10 to 30	-
Productivity	(tgb/hr)	95 to 105		62

[1] - bask = baskets of scrap/heat
[2] - several "best results" with K-ES were <300 kWh/tgb
[3] - tgb = tonne of good billets

Ferriere Nord achieved tap-to-tap times of less than 60 minutes and power-on times of 40 to 45 minutes, without the process being fully optimized. Therefore, tap-to-tap times of 45 minutes are believed to be realistic. Such heat times would nicely match caster speeds.

K-ES at Acciaierie Venete SpA[59]

The second plant to opt for the K-ES process is using the furnace described in Table XXII; it was built in 1988.

Table XXII: K-ES Furnace at Acciaierie Venete SpA[59]

Parameter		Size
Shell diameter	(mm)	5500[1]
Tap weight	(tonnes)	73 + 15% LH[2]
Transformer capacity	(MW)	35/38 (d/n)[3]
Electrode diameter	(mm)	600

Features:
- oval-shell bottom tapping (OBT)
- split shell design, upper part completely water-cooled
- current-conducting electrode arms, completely water-cooled
- "dog-house" enclosure
- swivelling turret arrangement for two slag pots
- level 1 and level 2 process control computers
- scrap preheating for 65 percent of the scrap
- six, 2MW, oxy-fuel burners
- supersonic, water-cooled oxygen lance (through the slag door)

[1] furnace shell diameter is 5500 mm with an extension of 700 mm on the long axis: therefore, the furnace cross section corresponds to a normal arc furnace with a shell diameter of 5920 mm
[2] LH = liquid heel
[3] d/n = day/night

In the K-ES mode, this furnace is fitted for bath agitation (porous plugs) and post-combustion. Based upon initial results, Ballandino et al[59] forecast the future specific consumption values shown in Table XXIII.

Table XXIII: Forecast of K-ES Effect[59]

Input Affected		Change	Value with K-ES
Electrical energy	kWh/tgb	-100	<300
Electrode	kg/tgb	-0.5	<2
Oxygen	Nm^3/tgb	+25	50
Coal/EAF dust	kg/tgb	+20	20

KCT's main competition for the K-ES process, it was pointed out, will come from Danieli and Badische Stahlwerke who apparently are also working on processes. Most of this work is going on in Austria and Germany.

Economic Considerations

The capital cost for adapting an existing EAF to a K-ES system was quoted as being about DM 4 million[60] (US $ 2.25 million at 1.8 DM/US$). This cost includes coal injection, post-combustion, and bottom stirring; our contact was not sure, but it may also include a license.

KCT has made no evaluation of the operating cost. Our contact was only able to provide us with an estimate based on their work at Tokyo Steel; operating in the K-ES mode produced steel for about US $11 less than operating as an EAF.

Licensing Agreements

KCT will license the K-ES process technology. The actual cost of the license will be based on the annual tonnage involved, payable in one lump sum.

Tokyo Steel has the marketing rights in Japan, KCT for the rest of the world. KCT would consider commercial EAF's of virtually any size for conversion to K-ES. Their market thrust will be mainly in Europe and North America. Although many furnace operators are implementing their own improvements, many EAFs still have very long tap-to-tap times and these are the ones that are prime candidates for K-ES.

Many plants have apparently indicated interest in the K-ES process, but KCT is proceeding cautiously in marketing it until the Ferriere Nord plant is completely proven. For the next year or so, only the two plants in Italy will be equipped with K-ES technology. Actually, KCT seem to have a capacity limitation in that four or five projects a year seems to be all they can handle, and blast furnace coal injection appears to be taking most of their time and energy.

The K-ES installation was off-limits to us to visit. However, our contact indicated that for any company that is seriously interested in K-ES technology for its plant, a visit could be arranged.

ENERGY OPTIMIZING FURNACE (EOF)

The EOF process was developed by the Korf Group and its Brazilian steel mill, Compania Siderurgica Pains, to replace three 28-tonne open hearth furnaces (2 operating, 1 on standby) producing the steel for 200 000 tonnes of billets a year. The furnace was designed to have a low capital investment cost and to be flexible in the type and proportions of metallics needed for the charge.

Process Development[61]

In 1976, when the Korf Group took over Compania Siderurgica Pains (CSP) in Divinopolis, Brazil, CSP was producing about 150 000 tpy of steel in four, 28-tonne, open hearth furnaces. These furnaces were charged with 70 percent hot metal produced in small, old, charcoal blast furnaces with the balance being cold pig iron and recycled scrap. After a thorough analysis of how to increase and modernize the steelmaking facilities, they decided that they would have to develop their own process. The program they followed is outlined below:

- 1978 - the introduction of the Korf Oxy-Refining Fuel (KORF) process with horizontal submerged tuyeres blowing oxygen into the 28-tonne open hearths
- 1982 - the installation of a 22-tonne EOF pilot plant at CSP, without a scrap preheater, to test important technical parameters. Results were so good that they decided to build a commercial EOF immediately
- 1983, January - start-up of the first commercial EOF, at CSP, with a 28-tonne tapping weight
- 1984, January - introduced water-cooled roof
- 1984, August - introduced removable furnace bottom car for quick bottom change
- 1986, May - start-up of multi-layer counterflow scrap preheater
- 1986, July - first commercial demonstration with 50 percent scrap charge
- 1987, July - start-up of "high scrap" operation with coal injection
- 1988, March - the second 28-tonne EOF began operating and the last open hearth furnace was shut down at CSP. CSP now produces all of their steel via the EOF process, with an annual production of about 450 000 tonnes.
- 1988 - a 60-tonne EOF began operating at Compania Siderurgica Aliperti in Sao Paulo, Brazil. This furnace, too, is charged with a mixture of (charcoal blast furnace) hot metal and scrap.

The first EOF is still in commercial use. It has also been used for all the development and test work - even the tests to demonstrate the capability of the EOF to process up to 100 percent cold steel scrap.

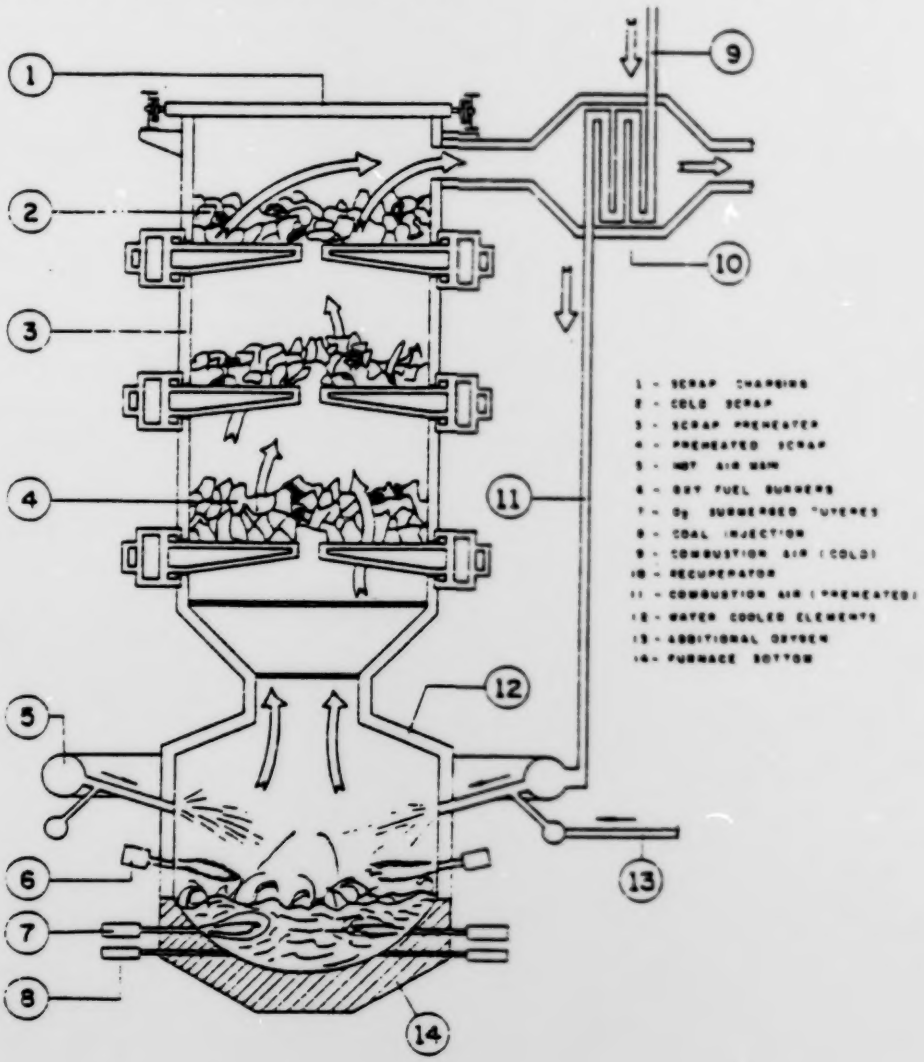
Process Description[61]

The EOF process is essentially a combined-blowing oxygen steelmaking process. Part of the oxygen is injected horizontally into the molten bath through specially designed submerged tuyeres; the remainder is blown into the furnace atmosphere above the bath through water-cooled injectors. The oxygen injected into the bath reacts with the carbon to form carbon monoxide (CO), causing vigorous agitation of the melt, thus enlarging the surface of the bath in contact with the oxygen-rich furnace atmosphere. The CO exiting the bath is burned to carbon dioxide (CO_2) within the vessel.

The heat generated by the oxidation of carbon to CO and CO_2 is used to melt scrap which has been previously preheated. The carbon for the reactions is introduced to the molten bath either as a constituent of molten pig iron from an external source or from solid carbon (-70 mesh coal fines or coke breeze) injected into the bath to form an artificial molten pig iron. The coal must be dried (or purchased ground and dried); the ideal "coal" would be <2 mm coke breeze.

The physical arrangement of the EOF may be seen in Figure 41.

Figure 41: Physical Arrangement of EOF[62]



The EOF system comprises a tilting furnace to allow slag-free tapping of the steel, a furnace exhaust gas temperature controller to control the maximum temperature of the gases to the preheater, a 3-stage scrap preheater, a retractable furnace roof, and a scrap bucket discharge mechanism. The entire furnace is operated under negative pressure, resulting in considerable air entering the furnace through the working door; about 50 percent of the after-combustion is with air. The scrap buckets have lids so that any dust generated when the buckets are unloaded is sucked into the dust collection system.

The EOF furnace is round and is lined with refractory up to the slag line. Water-cooled panels are used above the slag line. The roof is also water-cooled. The furnace itself looks like an EAF, except that the space above the bath is larger than that of an EAF of the same capacity. This additional space is required to allow the complete combustion of the CO exiting the bath.

The scrap preheater consists of three rectangular sections superimposed on top of each other. The preheater is supported independently of the furnace to allow for expansion. It is designed to allow hot gases to pass upwards through the three sections and preheat the scrap to 900°C. The scrap-filled chambers act as a packed bed filter and a portion of the dust in the exhaust gases is collected on the scrap.

The scrap preheater is refractory-lined. Water-cooled, hydraulically operated, retractable fingers in a comb-like grid arrangement support the scrap in each section. The scrap drops from one chamber to the next as required. A large opening in the furnace roof allows preheated scrap to drop into the melting furnace when the third (lowest) door is opened. Scrap pieces as long as 1.2 m and weighing as much as 450 kg can be charged to the preheater although a preferable mix would be shredded automotive scrap and a mix of No. 1 and No. 2 heavy and light scrap. No turnings are allowed.

The upper temperature of the gases leaving the furnace and entering the third stage of the preheater is controlled by a retractable water-cooled pipe grid that can be inserted into the gas stream as required. The movement of this pipe grid is interlocked with the movement of the fingers of the third stage of the preheater so that scrap cannot be dropped onto the grid.

Gas cleaning can be by whatever process is desired. The EOF operates under negative pressure even when scrap buckets are being emptied. This feature eliminates the need for a large dust collection system to evacuate the meltshop building. We were told that the waste gas volume is about one-third that of an electric arc furnace[63] (but this probably includes building evacuation).

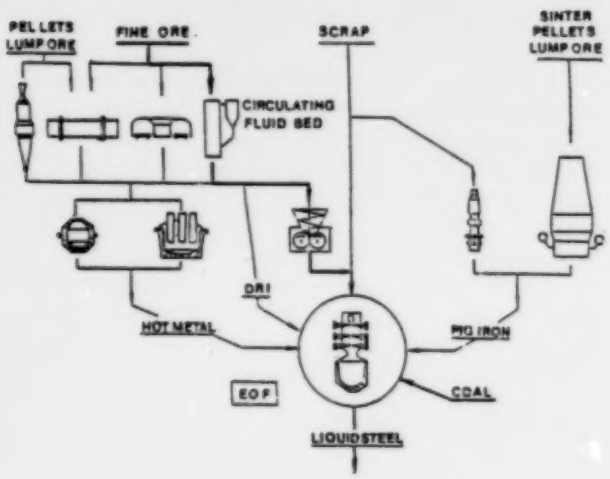
Lurgi has some thoughts that a circulating fluidized bed coupled with an EOF would be a good combination for producing steel. However, this concept has not progressed beyond the initial idea stage. Figure 42 summarizes the iron charge materials which can potentially be processed in the EOF process.

EOF Operation[61]

When the EOF is operated with a metallic charge of hot metal and scrap, all of the liquid steel is emptied from the tilted furnace using a slag-free tapping practice. After cleaning and closing the taphole, the furnace refractory is inspected and fettling, if needed, is undertaken.

Steelmaking begins with the charging of the scrap through the hole in the middle of the furnace roof and the charging of the hot metal via a launder. Fluxes are added as necessary by means of an automatic proportioning system consisting of pipes leading to a separate smaller hole in the roof.

Figure 42: Charge Materials - EOF Process[64]



Oxygen injection, both into the melt and into the free space above the melt, is begun immediately after the hot metal has been added. The heat generated by the oxygen reactions in the molten bath begins to melt the scrap. The CO which is produced by these reactions burns to CO_2 in the furnace atmosphere, generating additional heat that increases the temperature of the scrap exposed to the atmosphere above the bath. Much of this heat is also transferred to the bath to complete the process of melting the scrap. Once the scrap has been melted, the bath temperature increases.

The CO exiting the bath also causes the slag to foam and increase in volume. Eventually, the dam in the working door is broken open by the furnace operator and the slag flows out of the furnace (continuous flush).

The bath temperature at the end of melt-down is 1565° to 1580°C. Following deslagging, the refining and final heating phase begins - to achieve the aim tap carbon and temperature. Oxygen injection is continued until the carbon level has been sufficiently reduced; the temperature rises at a rate of 5.5° to 17C° a minute.

The carbon and temperature are measured at certain intervals and compared with the nominal carbon/temperature curve to determine the time to stop the oxygen injection. Since blowing time depends on the initial conditions of the melt (carbon and temperature) and on the intensity of injection (submerged oxygen, submerged carbon, top-blown oxygen), the refining phase can be computer-controlled. Minor deviations at the end of refining can be corrected by adding iron ore (to remove heat) or ferrosilicon (to add heat).

The reactions occurring during refining are the usual slag-forming reactions involving sulfur, phosphorous, silicon, and lime and other fluxing agents. To meet the sulfur and phosphorous specifications, the EOF operates with a slag basicity of 2.5 to 3.2. The slag has the same composition as BOF slag.

Tapping is performed easily and is controlled by means of the hydraulically operated tilting action of the furnace. The taphole is opened with an oxygen lance. When the desired weight of liquid steel has been tapped into the ladle, using load cells on the ladle car, the furnace is tilted back quickly until the taphole is above the slag/metal level. The taphole is cleaned, inspected, and closed with conventional magnesite refractory materials.

The autothermic charge ratio lies between 40 and 50 percent scrap, depending on the hot metal chemistry/temperature and the desired tapping temperature. When the EOF is to be operated above

the autothermic ratio, an external source of energy is required to replace the carbon and silicon normally contained in hot metal (i.e. less hot metal is being used). This energy is provided by carbon fines injected pneumatically into the molten bath through the innermost pipe of the submerged oxygen injection tuyeres.

When operating the EOF with 100 percent scrap, a liquid steel heel of 35 to 40 percent of the steel tapping weight is retained in the furnace along with the slag. After refractory inspection and fettling, the next heat is started; carbon fines (preferably anthracite or coke breeze) are injected to recarburize the bath to about three percent carbon, oxygen blowing is started, and the first charge of preheated scrap is dropped into the bath. Carbon and oxygen injections continue until all the scrap has been melted (additional scrap charges as needed). At that point, oxygen and/or carbon injection continues until the proper chemical composition and temperature for tapping have been achieved. The melting/refining period will typically require 50 to 55 minutes. Following tapping, the steel will generally pass to a ladle metallurgy station for final temperature and chemistry control.

EOF operating data obtained with different charge mixes are given in Table XXIV.

Table XXIV: EOF Operating Data as of May 1990[65]

Parameter	Operating Periods			
	A* kg/tls (%)	B kg/tls (%)	C kg/tls (%)	D kg/tls (%)
Metallic charge				
Hot Metal	675.0 (69.5)	562.0 (50.0)	335.0 (30.0)	0
Iron Scrap	329.0 (29.0)	0	0	0
Steel Scrap	131.0 (11.5)	563.0 (50.0)	781.0 (70.0)	1100.0 (100.0)
Total	1135.0 (100.0)	1125.0 (100.0)	1116.0 (100.0)	1100.0 (100.0)
Consumption				
Fuel oil kg/tls	<1	1 to 2	3 to 5	3 to 5
Carbon kg/tls	<2	15 to 20	50 to 60	85 to 100
Oxygen Nm^3/tls	60 to 70	70 to 80	90 to 100	110 to 135
Refractories (bricks) kg/tls	<1	3	4 to 5	5 to 6
Blowing time min	20 to 25	30 to 35	40 to 45	40 to 50
Heats/day	36	26 to 28	19 to 20	18 to 20

* Standard operating practice
Tapping temperature: 1680°C

The quality of the steel produced in the EOF is stated to be 100 percent comparable to that produced in a Q-BOP. The EOF has no limitation on the grades which it can make except that it is not good for making high chromium heats of stainless steel in the furnace.

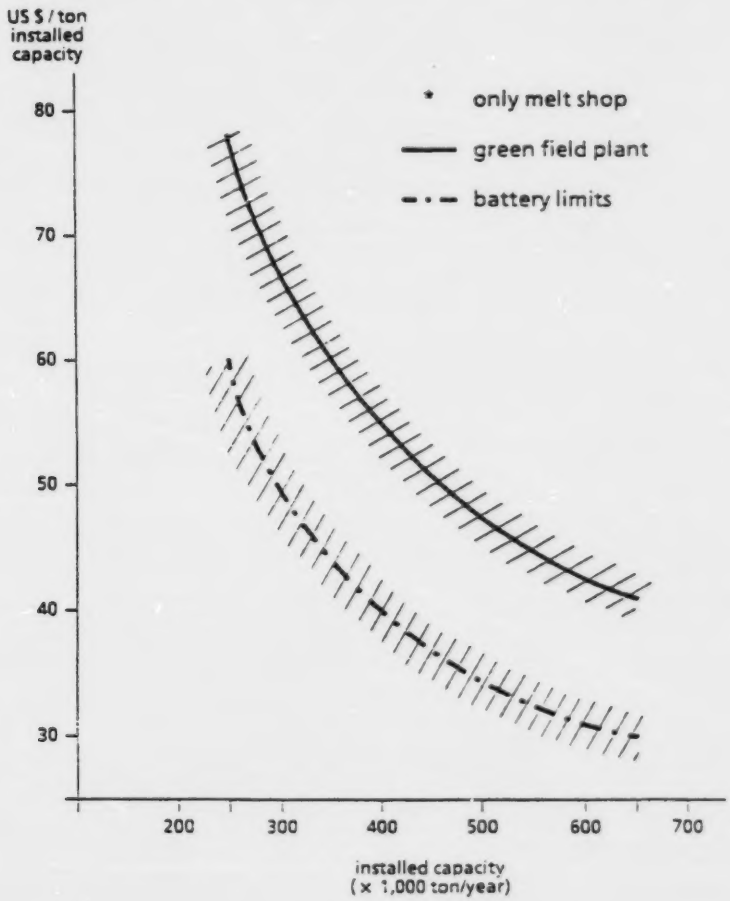
The initial consumption of refractories was 10 to 12 kg/tonne of steel produced. For over a year, however, it has been down to the range of 0.8 to 1.0 kg/tonne steel.[63] They effected this decrease by modifying the tuyere blocks, the way of blowing, etc.

The main maintenance problem they have run into in the plants where the EOF is operating has been the maintenance of the rest of the steel shop. In Brazil, for example, the EOF has run continuously for 2.5 to 3.0 months without stopping, 7 days/wk, 24 hours/day.

Economic Considerations

The capital cost of an EOF unit was quoted as being US $40 to US $70 an annual tonne installed on a greenfield site but within battery limits, and US $10 to $20 higher/annual tonne on a completely greenfield site (Figure 43). The higher range is for the high scrap utilization situation; the difference is primarily in the coal injection system which must be added in that case.

Figure 43: EOF* - Investment Cost[66]



Operating costs are stated to be sufficiently lower than those of the process replaced by the EOF that most plants would have a payback period of less than one year. In fact, Mr. Rollinger indicated that one year would be the worst case.[63] Such has been the situation to date.

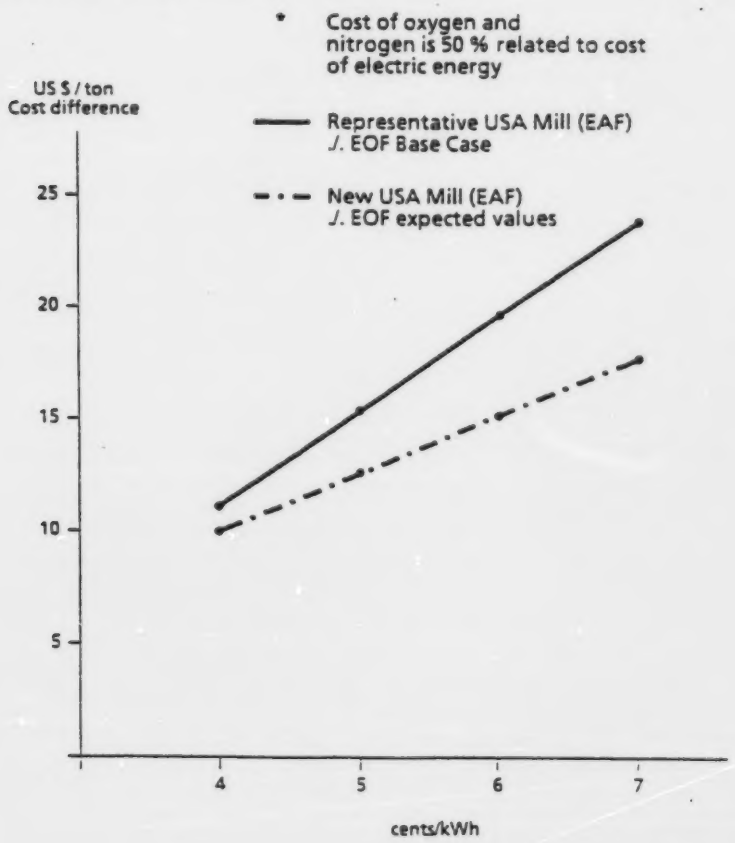
- The hot metal/scrap situation is compared to an open hearth of equal input and the improvement in operating cost (conversion cost only) is US $25 to US $40 a tonne produced.

- The all-scrap situation must be compared to the EAF; the differences are the following:
  - the EAF has electricity and electrode costs
  - the EOF has coal and oxygen costs; coal consumption is approximately 120 kg/t steel, if anthracite or coke breeze is used, but higher (with increased cost) if higher volatile matter coals are used, and oxygen consumption is about 135 Nm^3/t steel

- the use of coal would probably require the product at the EOF to be desulfurized.
- at 5.7 cents a kilowatt-hour, the operating cost advantage of the EOF over a modern all-electric arc furnace is stated to be approximately US $15/t steel, probably not counting desulfurization.

Since Canada no longer has any operating open hearth furnaces, the following cost comparison (Figure 44) is with the electric arc furnace.

Figure 44: Cost Advantage of EOF* vs EAF[66]



Licensing Arrangements

Each company which purchases one of these plants must purchase an operating license from Korf, based on the rated capacity of the plant.

Korf Lurgi Stahl Engineering GmbH (KLSE) are licensed to engineer and construct the EOF process.

KLSE's market thrust will be essentially Third World countries, the Eastern Block nations, and, in a few exceptional cases, Europe. This is not to say, however, that they will neglect North America.

KLSE expect to be able to market at least three plants a year, possibly four, each 500 000 to 600 000 t/y capacity for the next 10 years. They say 10 years because new technologies are expected to be developed that could supplant the EOF at some time.

The first EOF expected to come on stream in North America is the one planned for East Providence, RI. The engineering for this plant has been completed, but construction is being delayed because of a court hearing/ruling on the legal situation of the burning of coal in that city. (This is a legal action taken by the city to stop the construction of a thermal generating station there; it is based on a law passed by the city forbidding the burning of coal within the city. However, the city is prepared to grant an exception to the EOF process.) This should clear the last hurdle for the EOF and construction could start in the summer of 1990. (Start-up is scheduled for the end of 1991.) The East Providence plant will be the first EOF to use 100 percent scrap on a regular basis; it is designed to operate with a 20-tonne liquid steel heel. KLSE are pushing to get this plant completed as a demonstration unit; they believe that this plant will help the sale of their technology.

So far, the EOF has been used to produce steel for long products, but of higher quality than reinforcing bar. They were negotiating, at the time of our visit, with a producer of flat rolled products for two EOF units of 100 tonnes each. The output from these units would match the output from a thin slab caster.

At the time of our visit, KLSE were working on three to four projects besides the ones we knew about, with the signing of the next project expected within a matter of days. The latest listing of EOF projects is given in Table XXV.

Table XXV: EOF Projects[65]

No.	Location	Heat Size tonnes	Capacity tpa	Charge	Furnace	Scrap Preheater	Status
1	PAINS Divinopolis Brazil	30	220 000	50-70% hot metal 30-50% steel scrap/ iron scrap	fixed	3-stage	In operation since 12/1982
2	PAINS Divinopolis Brazil	30	220 000	50-70% hot metal 30-50% steel scrap/ iron scrap	tilting	2-stage	In operation since 3/1988
3	ALIPERTI Sao Paulo Brazil	60	400 000	50-60% hot metal 40-50% steel scrap	fixed	2-stage	In operation since 8/1988
4	TISCO (TATA) Jamshedpur India	80	520 000	50-70% hot metal 30-50% steel scrap/ iron scrap	tilting	2-stage	Under construction, start-up mid 1990
5	OSSI Rhode Island USA	40	250 000	100% steel scrap	tilting	3-stage	Under engineering, start-up end 1991
6	ITALY	60	450 000	40-60% hot metal 40-50% steel scrap	tilting	3-stage	Under construction, start-up mid 1991
7	OSTAG OZD Hungary	90	600 000	40-60% hot metal 40-60% steel scrap	tilting	3-stage	Under construction, start-up end 1991

RELATED CONSIDERATIONS

Any discussion of the present situation and trends in ironmaking processes cannot deal solely with smelting-reduction, blast furnace enhancements, coking technology and coal in steelmaking. Other aspects related to these processes have a bearing on both the present and the future. These aspects include:

- scrap quality and availability,
- direct reduction,
- coal markets, and
- environmental concerns, especially the "greenhouse effect".

Scrap availability has obvious importance in the various steelmaking processes, especially electric arc furnace steelmaking. Scrap quality is particularly important to those companies which are in, or will seek to enter or to expand in, the higher value-added steel products markets.

Direct reduced iron (DRI), the product of direct reduction processes, is a virgin iron product. It can be used to improve the quality of scrap-derived steel (e.g. EAF steel) by diluting the level of harmful residual elements contributed by the steel scrap. It is likely to realize increased utilization, especially as hot briquetted iron (HBI).

Coal markets are expected to change, probably gradually for the most part, but significantly. Increasing levels of coal injection, resulting in decreasing coke rates, spell lower demand for coking coals, with their rigid specifications, and a shift to greater demand for injection coal, with its most important specification being low price.

Global warming from the so-called "greenhouse effect" is currently a hot topic for many environmentalists. It is important that coal not become a scapegoat for this perceived problem.

Each of these topics will be discussed in order.

SCRAP QUALITY AND AVAILABILITY

Scrap Quality

Steel scrap is divided into two categories, circulating and purchased:

- circulating scrap, which arises from operations within the steel plant where it is collected for reprocessing through the steelmaking operation, and
- purchased scrap, which falls into two groups,
  - prompt scrap, which arises from the steel processing industry and which is frequently purchased by the steel company which sold the steel for processing, and
  - obsolete or capital scrap, which emanates from the scrapping of worn out, no longer usable, consumer and industrial goods, equipment, etc.

Circulating scrap is a known entity, as is prompt scrap if it is returned to the original producer. Obsolete scrap, which can come from virtually any source, is a major unknown unless it has been beneficiated and/or sorted by the scrap dealer and sold as a specific grade.

Conventional wisdom dictates that the quality of purchased scrap, especially the obsolete portion, is declining as more low-alloy, stainless, and coated (tinplate and galvanized) steels enter the market. However, this declining quality of scrap hypothesis has been criticized strongly, particularly by the scrap industry, as a perception rather than reality. A recent survey by the IISI[67] found the following national situations.

Japan

The perceived decrease in scrap quality has had no impact on the scrap-based steel producers in terms of the grades of domestically purchased scrap or in the level of tramp elements observed in molten steel produced from scrap-based EAFs. This situation is attributed to technological improvements, e.g. the installation of shredders, improved scrap segregation by steel type, and the introduction of such process improvements as ladle furnaces, degassers, etc.

United Kingdom

That the level of tramp elements in purchased scrap has been increasing over the last 60 years is widely accepted within the industry. The levels of Cu and Ni residuals in some steel products increased consistently between 1920 and 1945 and again in the late 1960s because of buoyant scrap demand and more alloy steels returning as scrap, but this trend generally stabilized in the 1970s. Problems with residuals are countered mainly by dilution with pig iron and improved selecting/processing of scrap.

United States

About 60 percent of the steel producers felt that the content of tramp elements in scrap was increasing at a significant rate. However, the levels of copper, nickel, and tin in the steel product showed more a trend towards decreasing slightly than towards increasing. This result is attributed to a combination of improved control of the tramp elements by the steel producers, increased usage of higher grade scrap, and better segregation and preparation of the scrap. It is quite possible that the overall quality of scrap could be declining while, at the same time, the

technology of scrap preparation is improving, thereby keeping the level of tramp elements in the final product within tolerable limits.

Canada

Canadian steel producers indicated some concern over copper, zinc, tin, and chromium residuals. Some scrap-based EAF operators indicated that DRI would provide a countermeasure should residuals in steel scrap become unmanageable. The overall feeling was that the consuming and supplying industries would have to improve sorting and segregation.

West Germany

Scrap users expect the quality of scrap to deteriorate and, therefore, more care will have to be exercised in collecting, sorting, and preparing scrap.

The Netherlands

Steel producers admitted that residuals in purchased scrap give problems but, because their biggest steel producer will extend continuous casting, efforts are being made to improve the quality of purchased scrap, i.e. to eliminate/decrease residuals and to increase scrap density.

Sweden

The trend has been for the level of residuals in purchased scrap to increase, especially since 1970. Greater coordination is required between the steel and scrap industries.

Luxembourg

Residuals in purchased scrap were reported to be of minor importance to this point in time, and the future trend is expected to be towards better quality, lower residual scrap.

Despite the perception, held generally among steelmakers, that tramp elements in purchased scrap are on the increase, the supporting evidence is somewhat inconclusive. Some deterioration in scrap quality did occur before World War II but, since then, the standards have been approximately maintained, with a little further deterioration in the period leading up to 1974, when demand was so buoyant. Most analyses of steel products produced today show little or no change in chemical composition from those produced 10 or so years ago. The steel industry has improved its methods of preparing and selecting scrap, using on-line computer systems to optimize the scrap mix, and, of even greater importance, has improved its technology in scrap usage and steel refining. Thus, although scrap quality may indeed be declining in terms of residual levels, this deterioration need not be passed along to the steel products, because of the greater vigilance of the scrap industry and the steelmakers.

The growth of EAF steelmaking has been almost as remarkable as that of BOF steelmaking. The prime reason has been the easy availability and competitive price of scrap. The phasing out of the high-scrap-consuming open hearth furnace and replacing it largely with the scrap-lean BOF effectively "released" scrap to the market that would otherwise have been purchased by the integrated steel producer, thereby facilitating the introduction and rapid growth of the EAF and the minimill phenomenon. As long as a surplus of steel scrap remains, EAF processing will continue to grow, provided the market exists for the additional steel.

Factors which may limit further significant growth of EAF steelmaking in the industrialized countries include:

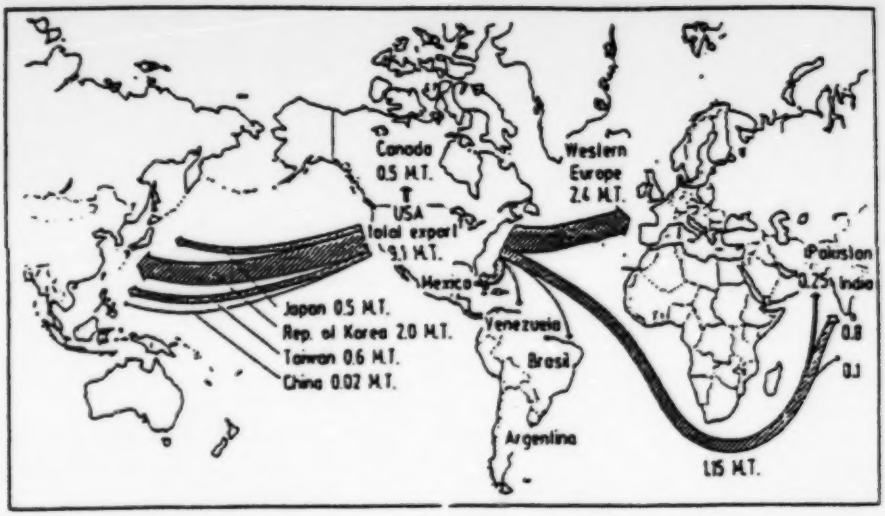
- the open hearth process has been largely eliminated in the industrialized nations, i.e. no further large release of scrap into the marketplace will occur, and so further replacement by the EAF is limited,
- the virtual no-growth forecast (~one percent/year) for the expansion of steel production capacity and the current surplus capacity militates against the building of more EAF capacity,
- the range of steel products available from a scrap-based minimill is still limited; some cold rolled sheet is being produced but this is the exception rather than the rule,
- the quality of purchased scrap is deteriorating in terms of residuals content, and this situation could eventually constrain significant expansion of the EAF process,
- the growth of continuous casting, with its decreased generation of circulating scrap, could increase the demand for purchased scrap by certain sections of the steel industry, thereby squeezing the EAF steel producers,
- advances in BOF technology, e.g. combined top and bottom blowing, coal injection, post-combustion, etc, give the integrated steel producer the option of increasing the scrap charge to the basic oxygen furnace; such a move could push the demand for purchased scrap to higher levels with consequent increases in scrap prices,
- the price of electricity, especially in industrialized countries, may prove to be a deterrent in the long run; electricity prices are largely outside the control of the steel industry and, in certain areas, they are sufficiently high to challenge the competitiveness of the EAF process, and
- the growth in EAF output is self-regulating; at high levels of scrap demand, prices increase rapidly and choke off extra demand and so, in the long run, high scrap prices will deter scrap-based processes.

Scrap Availability

A supply/demand study on scrap is generally carried out to examine the possibility of a surplus or shortage at some particular point in the future. However, beyond the short range of one to two years, such forecasts are of questionable value; scrap supply is largely determined by steel production, forecasts of which are based on trends. Trend forecasts are notoriously unable to predict the peaks and troughs of economic cycles; hence their inadequacy in the medium and long term outlooks.

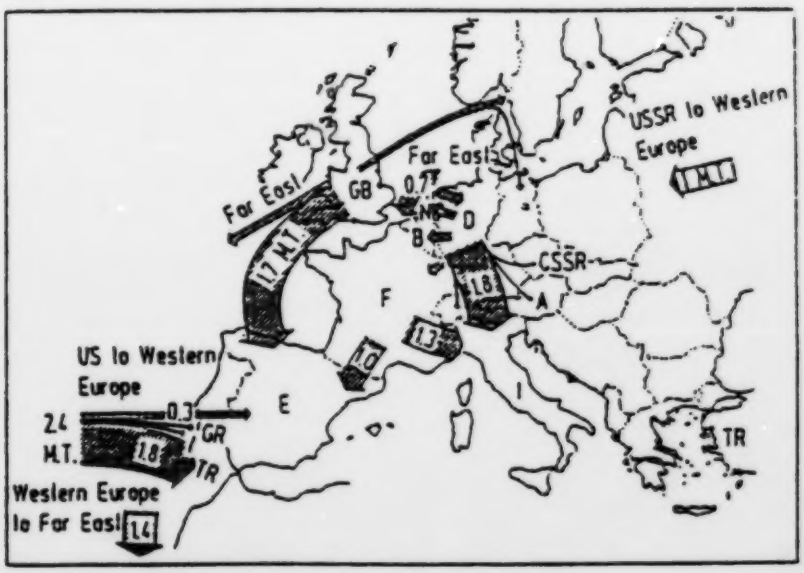
The generally held view is that scrap supplies are, and will remain, adequate for the foreseeable future. Any "shortage" of scrap can only be a short-lived occurrence caused by the rate of growth in demand rather than by an absolute shortage. The world scrap market and prices are determined mainly by scrap flows out of the USA and within Europe.[68] Figure 45 shows the export of scrap from the USA to the rest of the world in 1988.

Figure 45: Scrap Exports from the USA, 1988 (10^6 tonnes)[68]



Large fluctuations occur in scrap exports from the USA to Europe. Scrap exports from the USA to Italy and Spain have fallen off significantly. The largest share of the scrap exported from the USA, almost 80 percent, goes to Turkey as may be seen in Figure 46 which shows the scrap import streams to, and export streams within, Europe in 1988.

Figure 46: Scrap Import to, and Export Within, Europe, 1988 (10^6 t)[68]



Italy and Spain are heavy importers of scrap while the United Kingdom and West Germany have become net exporters. Specific situations are described below.

North America

North America is the major ferrous scrap exporting region of the world. The net exports are primarily from the USA, with Canada also being a small net exporter. The maximum potential level of exports from this region is likely around 11 to 12 million tonnes a year.

Southeast Asia

Traditionally, Southeast Asia has been a region of heavy steel scrap imports, a situation that is expected to continue but with a major shift. Japan is expecting to become self-sufficient in solid metallics by this year, 1990; indeed, a small surplus could be expected but this would be consumed either as increased scrap to the BOF or as increased output from EAFs. This decline in Japan's ferrous scrap imports will be offset by higher imports by South Korea, Taiwan (ROC), India, Singapore, and Thailand. Solid metallics imports by this region are expected to be substantial, about six million tonnes, in 1990. Within this region, China's (PRC's) and North Korea's steel production technology remains primarily oriented towards primary raw materials. Thus, neither is expected to make any lasting impact, either as an importer or as an exporter, on world trade in steel scrap.

Western Europe

The scrap situation in Western Europe is changing. Italy, Spain, and Turkey are the major steel scrap-deficit countries and are expected to remain so through at least 1995. On the other hand, the level of obsolete scrap available in some countries is increasing. This, coupled with the dim prospects for increasing demand for steel, has resulted in several countries becoming major exporters of ferrous scrap, albeit to other Western European countries such as Turkey, Spain, and Italy. While these intraregional scrap-exporting countries, i.e. France, West Germany, the UK, and the Netherlands, are expected to retain this position through 1995, Western Europe, overall, is forecasted to remain a net scrap-deficit region.

The overall conclusion from the IISI study[67] is that steel scrap supplies appear to be adequate now and for the foreseeable future.

Canada's Scrap Situation

The steel scrap recycling and processing industry has indicated[69] that scrap supply is adequate. However, a limitation may arise in the future from increasing demand for the low residual scrap required by EAF steel producers to make further inroads into the higher quality product markets. Examples of the steel residuals specifications faced by steel producers are given in Table XXVI.

Table XXVI: Residuals Specifications by Steel Grade[69]

Grade	Residuals % Maximum				
	Cu	Ni	Cr	Mo	Sn
Tinplate (Critical)	0.06	0.04	0.04	0.02	0.02
Drawing Quality Sheets	0.06	0.10	0.07	0.02	0.01
Commercial Quality Sheets	0.10	0.10	0.07	0.03	0.015
Low Carbon Wire	0.12	0.08	0.07	0.02	0.01
Cable and Spring	0.20	0.10	0.10	0.03	0.02
Special Bar Quality	0.25	0.12	0.12	0.03	0.03
Merchant Bar	0.35	0.15	0.15	0.04	0.03

Should supplies of low residuals steel scrap become insufficient to satisfy the demand, the price of these grades could escalate. However, the North American scrap market is free of tariffs and so the demand pressure for these grades may be eased somewhat. The other answer is dilution - by hot metal, cold pig iron, direct reduced iron (DRI), hot briquetted iron (HBI), or iron carbide (Fe_3C) - at an increase in cost. The hot metal, the cold pig iron, and/or the Fe_3C would require oxygen injection into the EAF melt, perhaps in substantial quantities, depending upon the amount of diluent necessary.

DIRECTION REDUCTION

Direct reduction processes can be either gas-based or coal-based. Representative processes are described in Volume II.

Direct reduced iron (DRI) is used at a number of EAF steelmaking plants, e.g. Hamburger Stahlwerke, Georgetown Steel, Sidbec-Dosco, etc, to produce higher quality end products. The most effective way of utilizing the DRI is to feed it continuously at full power once scrap meltdown has been achieved, and to feed it at such a rate that the furnace is virtually ready to tap when the last of the DRI has entered the melt[70]. Besides its several advantages, DRI usage also has some drawbacks, the most significant of which is the inevitable increase in slag volume. The absolute penalty varies with the gangue content of the DRI and the proportion of DRI in the charge. It amounts to about 44 kWh/tonne steel produced for every 50 kg increase in slag/tonne steel.[70]

An upsurge of DRI capacity is underway in various parts of the world. These new projects should increase total DRI capacity from its present almost 25 million tonnes to nearly 40 million tonnes. Much of this added capacity is earmarked for briquetted "merchant" DRI suitable for shipping to customers worldwide. For North American steelmakers, the most significant projects are those in Venezuela involving DRI briquette production primarily for export. Davy Dravo will build a one million tonnes/year FIOR plant there at Puerto Ordaz near the Orinoco River for the Corporacion Venezolana de Guayana (CVG) to reduce and briquette ore fines. Midrex installed 830 000 tonnes/year of HBI* capacity for CVG's Minerales Ordaz C.A. (MINORCA) plant, also located at Puerto Ordaz.[71] This plant, now called Operaciones al Sur del Orinoco C.A. (OPCO), began operation in January 1990 and is the first source of merchant HBI in the Western world. Its product is described in Tables XXVII and XXVIII.

Table XXVII: Typical Chemical Composition - OPCO HBI[71]

Component		Percentage
Total iron	Fe_T	92 - 95
Metallic iron	Fe^0	86 - 88
Carbon	C	0.1 - 0.3
Sulfur	S	0.01 - 0.03
Phosphorous	P	0.07 - 0.09
Gangue:	total	3.0 - 5.4
- Silica	SiO_2	~1.3
- Alumina	Al_2O_3	~0.8
- Lime + Magnesia	CaO + MgO	~1.2 - 2.8
Residual metals and metal oxides:		
Copper oxide	CuO	<0.002
Nickel	Ni	<0.002
Chromium	Cr	~0.005
Volatile metals and metal oxides:		
Lead oxide	PbO	<0.001
Zinc	Zn	~0.002

* HBI = hot briquetted iron. It is produced from DRI which is discharged hot from the reduction unit directly into a briquetting press to compact it into a uniform (size, shape, weight) product.

Table XXVIII: Typical Physical Characteristics - OPCO HBI[71]

Characteristic		Value
Briquette size	mm	30 x 50 x 110
Bulk density	t/m^3	2.6
Apparent density	gm/CC	5.5
Individual briquette weight	kg	0.6
ASTM tumbler index	% + 3.36 mm	98
Maximum moisture pickup	%	2.8

A marketing company, Bimarco, has been registered in Switzerland to handle the international marketing of the HBI product. Bimarco has already secured supply contracts with North Star Steel in the USA and is in active negotiations with many other US steelmakers, including LTV.[72] All of OPCO's output is slated for export (as is 50 to 80 percent of the output of the new FIOR plant); the USA is viewed as its natural market.

The main market opportunity for HBI is seen as a high quality alternative to scrap for charging into electric arc furnaces, and the price is pitched accordingly at 15 to 20 percent above that for heavy melting scrap.[72] One unofficial estimate of the price of HBI delivered to the USA is US $150/tonne[73], but this depends on the destination within the USA. More recently, OPCO has been reported as looking for a price of US $100 to $110 a tonne, F.O.B. Venezuela.[74] The suggestion is that the HBI would be used as a "sweetener" at 20 to 25 percent of the charge to provide the requisite steel quality - after everything else that can be done economically to improve scrap for the production of quality steel has been done. The consensus is that no more DRI-producing units will be built in Canada or in the other industrialized nations. The cost of natural gas, the source of the reducing gases, prohibits such installations from being economically viable.

Of course, one could consider a coal-based direct reduction process and several installations based on this technology are operating successfully in various parts of the world. So far, however, the annual production of DRI via coal-based direct reduction is very much lower than that via gas-based direct reduction. For example, in 1988, coal-based direct reduction plants produced only 1.03 million tonnes of the 14.16 million tonnes of DRI produced worldwide[75].

Various factors have favored the predominance of gas-based direct reduction. The gas-based processes are generally easier to control, the reactor availability is higher, the efficiency of energy utilization is higher, and the product is "cleaner", containing higher levels of carbon (1 to 3 percent) and lower levels of sulfur (up to 0.005 percent) compared to the coal-based processes. With the coal-based processes, process control has been difficult, the product fines contain 1 to 2 percent coal ash or char, even with the best type of magnetic separation, and, normally, the carbon content of the DRI is lower at about 0.20 percent and the sulfur content is higher at about 0.020 percent. The gas-based processes also have the advantage of requiring fewer physical steps, i.e. the reductant/fuel (natural gas) is piped to the plant under pressure and the end product does not have to be screened and passed through magnetic separation devices. Having said this, however, coal-based direct reduction processes can provide a viable option under the right circumstances, especially where there is a ready source of indigenous coal having the right characteristics for use in a rotary kiln.

It has been stated[76] that as the world proportion of coal as an energy source goes up and the reserves of oil and natural gas come down, the growth of coal-based direct reduction processes should become more marked. On the other hand, some consideration has been given to the gasification of coal to replace the natural gas feed to gas-based processes as the price of natural gas increases or its

availability decreases - to this point a too costly alternative. Some of the newly emerging smelting reduction processes may hold the key to utilizing gasified coal effectively, at least those which have separated the reduction function from the melting/smelting function.

One choice of diluent which is nearing reality is iron carbide[77, 78] (process description in Volume II). The 25 t/day iron carbide (Fe_3C) plant of Pact Resources started up on March 1989. Other agreements provide for two plants with a capacity of 350 000 t/yr each to be built in North or South America.[79] Cost savings to the steelmaker of 20 percent compared to scrap are claimed.

The degree of need to dilute residuals in scrap-based steelmaking varies, depending upon the availability of scrap of the right quality in the right quantity. It is this situation that will control growth in the use of diluents such as DRI.

COAL OUTLOOK

Coal Importers

Western Europe

The anti-coal lobby is taking every opportunity to frighten the man-on-the-street with the currently fashionable bogeyman of global warming. In Denmark and Italy, obtaining acceptance of any favorable view of coal for new power generation is difficult. In the UK, Mrs. Thatcher has been quoted as having said that Britain should build lots more nuclear power stations "because coal is responsible for the greenhouse effect".[80]

In 1987, hard coal production was as follows:

United Kingdom	104 Mt*
West Germany	82 Mt
Spain	14 Mt
France	14 Mt
Belgium	5 Mt
	219 Mt

Without its government assistance, much of this protected production would be unable to compete against imported coal. The greatest market distortions occur in the UK and West Germany, with total coal imports of only 10 Mt and 8 Mt, respectively, in 1987.[81]

The Australian Bureau of Agriculture and Resource Economics (ABARE) has estimated that only about 66 Mt of British Coal's production, out of a total of 103 Mt in 1986, would have been profitable without government assistance. Had a free market economy been operating, the UK would have imported 37 Mt steam coal that year, all other circumstances being equal, instead of merely 4 Mt.

The Australian government's preliminary analysis indicates that if all the support measures which directly impact coal production in Europe were to be phased out, the total average demand for imported steam coal could rise to 180 Mtpa by the year 2000 (1986 imports amounted to 80 Mt). Furthermore, the import tonnage of coking coal could be as high as 90 Mt (42 Mt in 1986).[81]

Germany will be the key influence on the shape of the European coal market in the next 15 years. Their policy has been to maintain a strong home coal industry, this being their only natural resource. The cost to the taxpayer has been staggering - 10 billion DM (approximately US $5.6 billion) a year; the justification is a combination of strategic and social reasons.[82]

By 1992, the sale of subsidized coal into the EEC is slated to end. The major beneficiaries of reduced coal support measures in Europe would likely be the coal producers in the USA, South Africa, Colombia, and Australia. However, Europe is also seen as a potential opportunity for Canadian coal producers; at worst, it offers a stable market but, more likely, an improved market, over the next 10 years.

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* Mt = million tonnes: Mtpa = million tonnes per annum

Mexico

Mexico could become a significant importer of steam coal,[80] saving their higher-value oil for export.

Brazil

Brazil may have to lift its ban on the import of steam coal to meet its growing demand for electricity.[80]

From April 1988 to March 1989, Brazil imported about 10 Mt coking coal primarily from four suppliers as follows:

USA	46%
Poland	21%
Canada	16%
Australia	14%
Others	3%

Diversification of supply sources is a deliberate policy of SIDERBRAS. Domestic coal represents only 8 percent of Brazil's coking coal consumption.[83]

The market for coking coal should expand as new coking capacity comes on-stream in 1993, at Companhia Siderurgica de Tubarao (CST) - 1.6 Mtpa coke, and in 1994, at Acominas - 1.0 Mtpa coke. Furthermore, USIMAR is said to be in the advanced studies stage towards the construction of the Maranhao Steel Mill which will have coke requirements of 2.0 Mtpa in stage 1 increasing to 3.0 Mtpa in phase 2. Should all these projects come to fruition, the need for coking coal will increase by about 7.6 Mtpa.

USIMINAS plans to begin coal injection in 1991 at the rate of about 100 kg/thm. Cia Siderurgica Nacional (CSN) plans to inject natural gas at the rate of 28 Nm^3/thm. Both of these changes could affect the market for coking coal. As well, the steel companies are looking to utilize anthracite in the sinter mix. So the Brazilian coal market may be changing, which warrants the attention of Canadian coal producers.

Asia[80]

Asia represents a huge potential market for steam coal. For example, two billion has been estimated as the number of people there who still rely entirely on open fires for cooking. With increasing standards of living, electricity becomes a natural replacement, as well as providing other amenities. Nearly all of this additional electricity that is going to be used will come from coal.

Asian industrialized countries have great concern over ensuring reliable long-term supplies of ever-increasing quantities of fuel. This concern lies behind the attitude of the Japanese, Korean, and Taiwanese towards long-term contracts and direct investment in joint venture projects in coal mining - with established suppliers.

Japan[84]

In 1988, Japan imported about 100 Mt coal, of which 74.7 Mt was metallurgical coal. Canada's share of this market was 19 Mt metallurgical coal and 1.5 Mt steam coal.

The Japanese steel industry has decided to stop using uncompetitive Japanese domestic coal after fiscal year 1990. They will also make a major effort to import, and use, more lower quality, less costly coals than ever before in their ongoing push to reduce raw materials' costs.

The Japanese steel industry has increased the ratio of semi-soft coking coals in its coking blends. In 1980, they imported 2 Mt of semi-soft coking coal - 3 percent of their total coal consumption; by 1988, they were importing 13 Mt - >20 percent of their coking coal requirements. The policy of increasing this ratio is being maintained.

The semi-soft coking coal is being purchased overwhelmingly from Australia (about 70 percent of total procurement). South Africa is a second major source, supplying 15 percent. Semi-soft coking coal imported from Canada amounts to <10 percent of this market.

Korea[80]

Besides being a growing market for coking coals, Korea is also a growing market for steam coals. South Korean government policy states clearly that more coal-fired power plants will be built and, eventually, bituminous coal will become one of the major fuels for power generation. The electric power supply objective is 40 percent from nuclear generating stations (currently 54 percent), 40 percent from coal stations, and 20 percent from others (hydro, oil, etc). Imports of steam coal, presently about 6.5 Mtpa, are expected to rise to 15 Mtpa by 1995 and to 21 Mtpa by 2000.

Coal Exporters

Australia

Australia ranks first in the world among coal exporters. In 1987-88, Australia exported coals to 43 countries as follows:

- 17 countries ..... >1.0 Mt each (94%)
- 3 countries ..... 0.5 to 1.0 Mt each (2%)
- sundry other minor importers ..... (4%)

Details are given in Table XXIX.

Table XXIX: Distribution of Australian Coal Exports, 1987-88[85]

Destination	Metallurgical Mt	Thermal Mt	Total Mt	%
Japan	27.2	21.5	48.7	47.5
Asia/Pacific:				
Korea Republic	3.8	4.1	7.9	
Taiwan	2.8	4.8	7.6	
India	3.1	0.4	3.5	
Hong Kong	-	2.9	2.9	
Indonesia	-	1.4	1.4	
Pakistan	0.6	-	0.6	
Philippines	-	0.4	0.4	
Other	0.5	0.7	1.2	
Total Asia/Pacific	**10.8**	**14.7**	**25.5**	**24.9**
Europe & Mediterranean:				
Netherlands	1.2	3.5	4.7	
UK	2.8	0.7	3.5	
France	2.4	0.8	3.2	
Italy	2.3	-	2.3	
Turkey	2.2	0.1	2.3	
Denmark	-	2.1	2.1	
Romania	1.8	-	1.8	
Spain	1.0	0.1	1.1	
Sweden	0.6	0.5	1.1	
Belgium	0.8	0.2	1.0	
Israel	-	0.7	0.7	
FRG	-	0.6	0.6	
Other	1.1	0.8	1.9	
Total Europe	**16.2**	**10.1**	**26.3**	**25.7**
Americas:				
Brazil	1.3	0.1	1.4	
Other	0.4	0.2	0.6	
Total Americas	**1.7**	**0.3**	**2.0**	**2.0**
Total All Countries	**55.9**	**46.6**	**102.5**	**100**

Joint Coal Board, 1988a

International Energy Agency (IEA) projections for Australian energy use, domestic coal use, and exports are produced periodically in the series of country energy assessment reports. The latest of these is contained in IEA Coal Information 1989 and has been used, in conjunction with other forecasts, to develop a consolidated demand forecast for Australian exports, Table XXX. Pulverized coal injection (PCI) requirements are included in the metallurgical demand category, although the types of coal used for injection do not necessarily possess coking characteristics. Likewise, the thermal coal category is not confined to steam raising but includes such coal uses as cement manufacture, etc.

Table XXX: Export Demand Forecasts for Australian Coals[85]

Coal Category	Exports, Mt					
	Actual		Forecast			
	1987	1988	1990	1995	2000	2005
Metallurgical coal	49.8	55.8	55	55	60	N/A
Thermal coal	45.9	46.5	50	60	70	80
Total export	95.7	102.3	105	115	130	N/A

(IEA/OECD 1989, DPIE 1988 and IEA Coal Research derived forecasts)

South Africa[80]

South Africa is the eighth largest coal producer in the world and the third largest exporter. Total coal production in 1988 was 173.6 Mt, of which 43.6 Mt was exported. Price gives South Africa an advantage that ensures its continuing role as a major world supplier.

United States of America

The USA dominates the European metallurgical coal market, with a 33 percent share of total imports.[82] They also dominate the Canadian and USA markets for metallurgical coal.

Poland[82]

Poland is a major supplier of metallurgical coal to British Steel Corporation - 15 percent of their requirements. (By way of comparison, Canadian coals comprise about 10 percent.) However, Polish coal exports are expected to fall significantly over the next five years.

Eastern Europe[80]

Future exports of coal to the West are expected to be on-again, off-again, with increases in coal production being absorbed rapidly by increasing domestic demand as standards of living rise. Thus, the USSR, as well as Poland, may be exporting less coal to the West.

People's Republic of China

China is one of the world's largest producers of coal (and a significant producer of oil, as well). Of the total production in 1987, bituminous coal accounted for 75 percent (49 percent of which was coking coal), anthracite about 21 percent, and lignite about 4 percent.

Coal exports represent only about one percent of China's coal production, but China is ranked seventh among the world's coal exporters - after Australia, the USA, South Africa, Poland, Canada, and the USSR. China's coal exports essentially doubled from 1955 to 1965 (10 years), and again from 1965 to 1985 (20 years), and yet again from 1985 to 1988 (3 years):[86]

1955 . . . . . 1.63 Mt
1965 . . . . . 3.36 Mt
1985 . . . . . 7.57 Mt
1988 . . . . . 15.9 Mt

China is expected to become an increasingly active player in the export coal market.[82] Undoubtedly, the resurgence of China brings with it increased demands for coal internally, and satisfying these demands must be their first priority. However, at the same time, the rebuilding of the country requires foreign currency and coal is a commodity which is converted easily into dollars. A port system exists which could easily handle 50 Mtpa of coal exports, and so, as improvements to the railroad systems come on stream, increasing flows of Chinese coal onto the world market must be anticipated.

Indonesia[87]

Both the production and export of Indonesian coal will rise considerably in the next 5 to 10 years and, during this period, Indonesia is expected to move from being a modest producer of coal to join the ranks of the middle level coal producers and exporters. By the mid-1990s, production levels could be 4 to 5 times what they are today. Indonesia is eyeing the steam coal markets in Japan, Korea, Taiwan, and its ASEAN neighbor countries.

New Zealand[80]

In 1989, the government-owned coal industry was reported to be for sale. Japanese, Korean, and Taiwanese interests were assumed to be on the rather long list of interested potential bidders.

Colombia[88]

Colombia has ambitious plans to expand its steam coal trade which in 1987 amounted to >11 Mt, about 7 percent of the seaborne coal market. They foresee an increase in the coming years in steam coal demand such as will bring the seaborne trade close to 320 Mt by the year 2000, a growth of 100 Mt. They are targeting to fill 20 percent of this growth, i.e. they are targeting a 10 percent share of the total seaborne trade by the year 2000.

By 2000, Colombia's current plans for steam coal export projects call for a total production of 27 to 33 Mtpa; however, production could be considerably higher than that. If plans for the El Descanso and other projects are feasible, production could reach >40 Mtpa by 2000. Moreover, the El Cerrejon output can reach 30 Mtpa if the east pit is developed. Thus, Colombia could reach a total export potential of 60 Mtpa by the end of this century. Apparently, none of these expansion projects has subsidies, tax relief schemes, or special treatment - they have to be competitive on their own.

Colombian steam coal is stated to be of good quality and the mines are close to the sea and to European customers.

Venezuela

Venezuela exported 0.8 Mt steam coal in 1987.[88] According to present plans, they have the potential to produce and export >12 Mtpa coal by 2000.[89] While Venezuelan coals are primarily steam coals, coal from some of the projects can be considered for some metallurgical applications, such as PCI or as semi-soft coking coals.

Venezuela is also developing Orimulsion as a direct competitor to steam coals for use in thermal generating stations. Orimulsion is an oil/water emulsion comprising about 70 percent natural bitumen, 30 percent water and a small quantity of surfactant (nonyl phenol ethoxylate).[90] It is being produced from the vast deposits of bitumen in Venezuela's Orinoco Heavy and Extra Heavy Oil Belt by Bitor, a subsidiary of the national company, Petroleos de Venezuela SA (PDVSA).[91] Production of Orimulsion in Venezuela could reach 10 Mtpa by 1995.[80]

Peru[80]

Peru is likely to be a modest exporter of anthracite.

Canada

In 1988, the Canadian coal industry mined a record 71 Mt coal of all ranks, from anthracite to lignite.[92] That year, 54 Mt coal was consumed in Canada, 85 percent of it to generate electricity; electric utilities burned 37.5 Mt domestic coal plus 8 Mt imported coal.

The National Energy Board's predictions to the year 2005 represent a relatively conservative growth in electric power consumption of about 3.5 percent a year. Accordingly, 40 000 MW of new capacity will be needed nationwide. Over one-half of this increase is projected to come from hydro, 16 percent from nuclear, 13 percent from coal, and 13 percent from other sources, including natural gas and oil. The result will be an additional 16 Mtpa, approximately, of coal being burned in 2005. This, coupled with the existing burn, 46 Mtpa in 1988, means a total burn of 62 Mtpa in 2005, possibly even more as emerging clean coal technologies make the burning of coal more acceptable. Thus, considerable growth potential for the thermal coal market exists in Canada.[93]

Coal is a vital component of Canada's exports. In 1988, Canada's coal exports amounted to 32 Mt, nearly one-half of what was produced in this country.[92] It is Canada's single largest export commodity to both Japan and South Korea.

More than 90 percent of the Canadian coal exported is metallurgical coal. From 1980 to 1988, world crude steel production increased by 8.6 percent. Another notable trend over that same period was that the production of crude steel in developed countries decreased while that in developing countries increased considerably, Table XXXI.

Table XXXI: Change in Crude Steel Production, 1980 to 1988[84]

Country	Production Change %
Japan	-5.1
USA	-11.5
West Germany	-6.5
Canada	-4.4
Brazil	+60.4
Korea	+123.2
China	+59.4
USSR	+10.2

Such changes inevitably mean a shift in the market for coking coals.

Canada's share of the total quantity of coking coal purchased by the Japanese steel industry actually increased from 15 percent in 1980 to >25 percent in 1989. This situation resulted from the successful efforts of Canadian coal suppliers to respond to the Japanese steel industry's expectations - which will certainly not diminish in the future.

The most immediate threat to the metallurgical coal market of Canadian coal producers is the increasing impact of coal injection upon the need for coke. This situation is deleterious in two ways:

i) the decreased requirement of metallurgical coals with their stringent specifications, and
ii) the injection coal specification of greatest importance is price, which drastically increases the number of potential suppliers.

The impact of all the other technologies discussed in this report pales by comparison to the probable impact of coal injection.

Some mitigating effect may be felt as the potentially huge market that exists for Canadian metallurgical coals in the industrialized and industrializing countries of the Pacific Rim continues to open up. The Korean and Taiwanese steel industries are still expanding. India and perhaps even China may become significant markets since both are behind Japan, Korea, and Taiwan in steelmaking technology.

Several suggestions have been aimed at the Canadian coal industry:

- Quality Assurance[82]
  The ultimate end point of quality assurance is the customer never having to carry out his own analysis because he can rely on the supplier. Coal companies, as other companies, must have in place the systems to ensure that they deliver to the agreed specifications.

- Image[80]
  The universal problem with coal is the poor image it has in the mind of the general public - acid rain, the "greenhouse effect", smoke and grime, and just sheer basic ignorance of what coal is and what it contributes to modern life. Coal needs a sustained public relations campaign to brighten its image - just as is being done by the nuclear, oil and gas, etc, industries.

- Product[84]
  - Pay attention to the trend in customers' requirements regarding coal quality.
  - Maintain price competitiveness in the international marketplace at all times.
  - Remain flexible with respect to the market trend, e.g. smelting-reduction, etc.

"GREENHOUSE EFFECT"

The presence of greenhouse gases in the atmosphere is essential for the preservation of life on Earth through their moderating effect on the climate. Average world temperature is around 15°C, but would plunge to -23°C without greenhouse gases. These gases, water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), chlorofluorocarbons (CFC), nitrous oxide (N_2O), and ozone (O_3), allow the free passage of sunlight to the Earth and then trap the radiated infrared light, resulting in the warming of the Earth's surface.

The contribution of the various greenhouse gas emissions to the total greenhouse effect from human activities from 1980 to 1985 was estimated by Warwick (1988)[94(1)] to be:

CO_2	56 percent
CFC	24 percent
CH_4	14 percent
N_2O	6 percent

These data would be modified by the contribution from increases in O_3 in the lower atmosphere, the product of reactions among other pollutants.

Projected increases in the "greenhouse effect" are a direct consequence of population increase and improved living standards. Greenhouse gas concentrations have increased in the atmosphere by 50 percent in the past century. They continue to increase, CO_2 at 0.4 percent per annum, methane at 1.3 percent, and CFC (freon-II) at 5 percent. Although increases to date have not caused a detectable change in the Earth's temperature or climate, fear is mounting that the continuing increase in greenhouse gas emissions may bring about a future temperature increase.

Recognition of the greenhouse effect is complicated by the complexities of the Earth's climatic system - atmosphere, ocean, ice, land. Climatic change occurs anyway as the result of many natural processes. The problem is to distinguish between a change induced by human activities from one due to natural variations in global climate. To date, because of uncertainties in some aspects of the data used and the mechanisms involved, it is impossible to predict, with any accuracy, the response of the global climate to increased concentrations of the greenhouse gases from human activities.[94] Certainly, the results of climatic model experiments broadly agree that global warming will occur in the next century. But as yet no conclusive evidence exists that increasing concentrations of greenhouse gases are resulting, or will result, in a climatic warming.

The situation introduces a predicament for policy- and decision-makers in both government and industry. On the one hand, the magnitude of the issues involved is such that an ill-founded course of action could impose substantial unnecessary penalties on mankind, retarding economic development and restricting energy options. On the other hand, the seriousness of a potential rapid climate change calls for the prudent implementation of reasonable mitigating measures.[95]

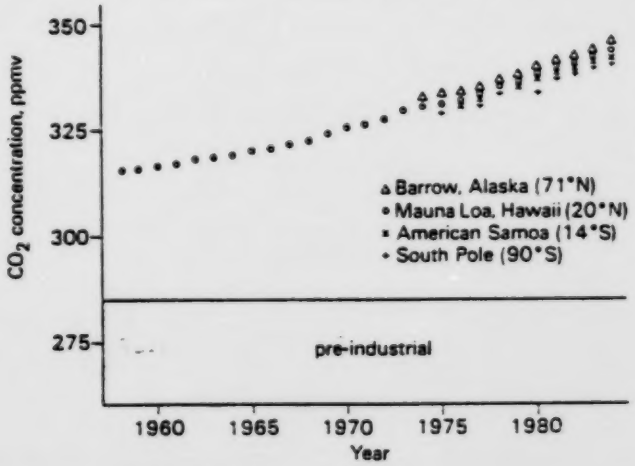
If the emission of greenhouse gases really is a problem, then it is a global problem and must be tackled globally. US utility coal use, one target of early legislation, contributes less than four percent of the world's production of man-made carbon dioxide. Action by the USA, alone, or by Canada, alone, will do less than little to impede any global warming, but it would do much towards having the North American economy finish a distant third to Europe and Asia in the next century.[96] What we don't need is a knee-jerk reaction by our legislators in response to uninformed pressures. To enable the world to cope with the future, the nature and magnitude of the perceived potential problem must be clarified, any strategies adopted must have the least adverse effect on mankind, and the greenhouse gas emissions must be minimized by maximizing the efficiency of the processes that emit them.

Any approach to the global warming issue must allow for continuing dependence on all major fossil fuels. Economic development and the well-being of the world depend crucially on energy, and non-fossil fuel can supply only a minor component of the world's energy needs for the foreseeable future. Because of its vaster reserves, compared to oil and gas, coal must continue as a major energy source.

At the Toronto Conference on the Changing Atmosphere held in June 1988, the Conference advocated a reduction in CO_2 emissions by approximately 20 percent of 1988 levels by the year 2005 as an initial global goal. One-half of the reduction would be sought from energy efficiency and other conservation measures, the other half by modifications in energy supplies.[94]

In 1984, the emissions of CO_2 from fossil fuels, cement manufacture, and land exploitation had reached approximately 6 to 8 gigatonnes of carbon a year (Gt C/yr). These emissions appear small at first sight compared to emissions from the biosphere (~110 Gt C/yr from land and ~90 Gt C/yr from oceans). They are, nevertheless, producing a perturbation to the Earth's atmosphere as evidenced by steadily increasing concentrations of CO_2 worldwide, Figure 47, (Bolin and others, 1986).[94(2)]

Figure 47: CO_2 Concentrations in the Atmosphere[94]



(MARC, 1987)

Considering the sources of CO_2 from human activities, the portion from coal amounted to 2.1 Gt C in 1984, i.e. 27 to 34 percent of the total man-made CO_2 emissions of 6 to 8 Gt C. The spread in the estimate arises mainly from uncertainties in emissions from deforestation and land exploitation. If CO_2 is indeed responsible for 56 percent of the total greenhouse effect, the contribution from CO_2 emissions from coal combustion to the greenhouse effect was about 15 to 19 percent. Only about one-half of this quantity is attributable to coal-fired power generation (the proportion of coal used worldwide for power generation was 49 percent in 1986)[94(3)]. Hence, it may be concluded that the contribution to the greenhouse effect of coal-fired power generation was about 8 percent of the total: that from blast furnace ironmaking was significantly less than that.

Coal reserves are much greater than those of oil or gas and, with time, this situation will likely impact on the relative prices and, hence, on utilization. Sufficient accessible coal is available that supply will not be a constraint on coal utilization in the foreseeable future. The major potential constraint would be the passage of environmental legislation in the main coal-consuming countries which would have the effect of favoring other energy sources such as, for example, nuclear power.[94] What might happen

to the integrated steel industry in such countries is difficult to say - at best it could be put into an uncompetitive situation, at worst it could be forced to cease operation.

The regional patterns of energy consumption and, hence, CO_2 emissions, are changing as newly industrializing and centrally planned countries increase their use of fossil fuel (Table XXXII).

Table XXXII: The Changing Patterns of Global CO_2 Emissions[94]

	1950		1980	
	Gt C	%	Gt C	%
North America, Western Europe, Japan and Australia	1.14	70	2.49	48
Centrally planned countries	0.31	19	1.72	33
Newly industrializing countries	0.09	6	0.63	12
Other	0.08	5	0.33	7
Total	1.62	100	5.17	100

In absolute terms, CO_2 emissions increased in all regions between 1950 and 1980. However, the relative proportions from North America, Western Europe, Japan, and Australia declined, while those of the rest of the world increased.

Figures 48 to 50 (Marland and others, 1988)[94(4)] show trends of CO_2 emissions in three representative countries. Figure 48, China, exemplifies an industrializing country with a fast growth rate using mainly coal as an energy source, and increasing its CO_2 emissions. Figure 49, Canada, represents an industrialized country with increasing use of coal. Similar trends are found in Australia and Denmark. Figure 50, the Netherlands, represents an industrialized country with increasing use of natural gas. In Finland, Spain and the USA, CO_2 emissions have decreased despite increasing use of coal.

Figure 48: Trends in CO_2 Emissions - China (Mainland)[94]

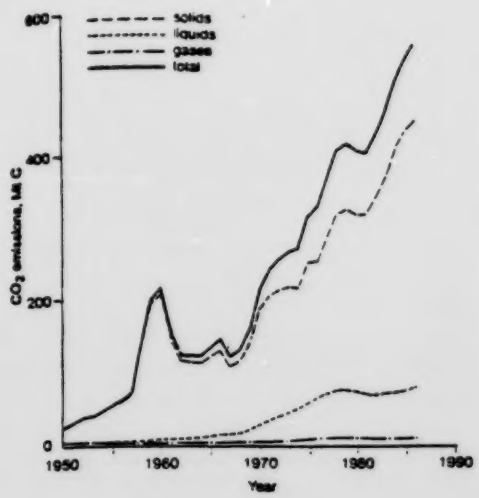


Figure 49: Trends in $C0_2$ Emissions - Canada[94]

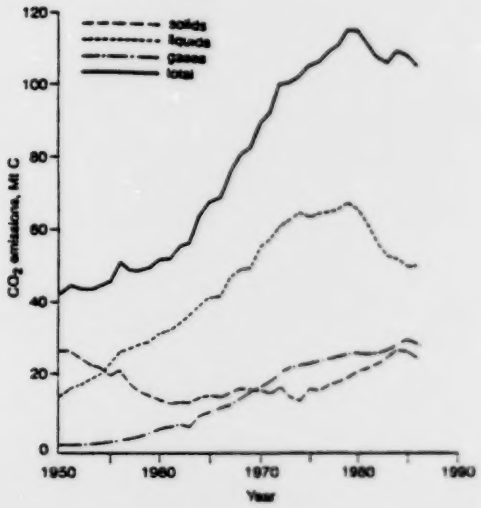
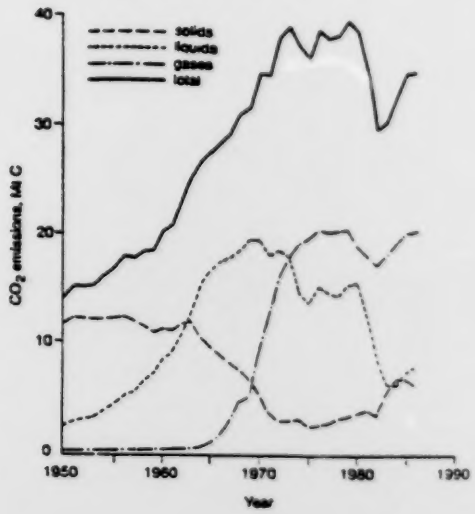


Figure 50: Trends in CO_2 Emissions - The Netherlands[94]



None of the trends in Figures 48 to 50 can be extrapolated into the future. Projections, made since 1981, of CO_2 emissions as carbon in the year 2050 range from 2 to 20 Gt C annually - compared to the current 5 Gt C/yr - a huge uncertainty. The one certainty is that future emissions of CO_2 to the atmosphere will depend on political, economic, technological, and social developments, influenced by increasing awareness of the costs and consequences of a choice of strategies.[94]

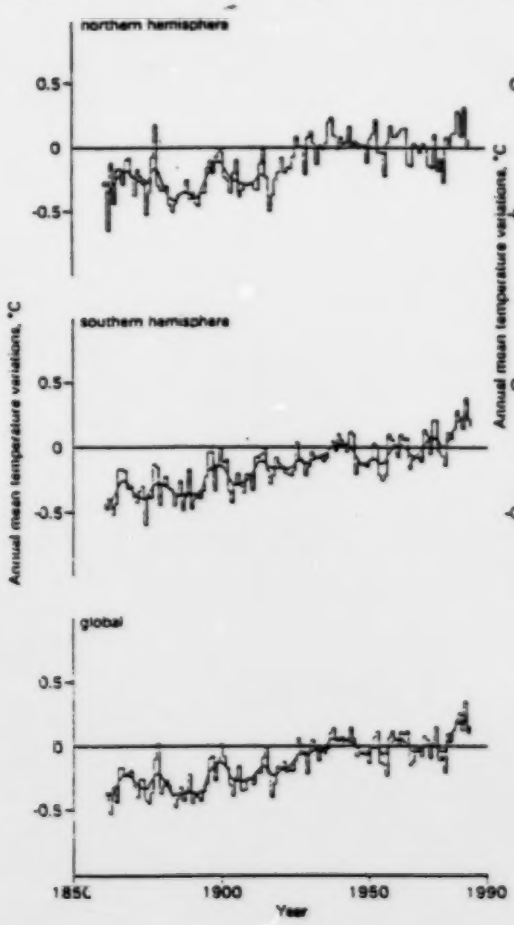
The time at which climatic change may become an urgent problem depends both on future rates of increase of emissions and on the uptake of CO_2 in the various storage sinks. The warming effect of the greenhouse gases on climate is being investigated by climatic model experiments, but even the most sophisticated models suffer inadequacies in the representation of clouds, hydrology, and oceanic circulation, as well as by the sheer size of the problem of modeling the whole of the Earth.

Model results indicate a global rise in surface temperature of 1.5° to 5°C for a doubling of the preindustrial CO_2 concentration in the atmosphere (expected in 2050, although the equivalent effect could be felt as early as 2030 if the Montreal protocol proves ineffective in reducing CFC emissions). This warming should emerge above background variations of ±0.5°C, i.e. an increase of 1°C, at, or soon after, 2000.[94]

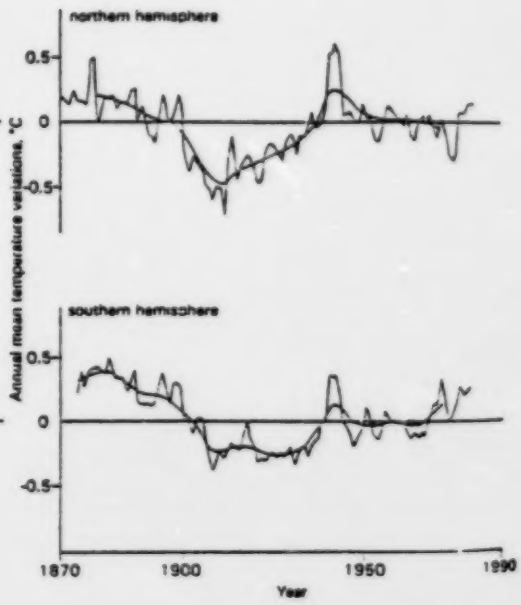
Model results agree that the largest equilibrium warming would occur in regions of high latitude during winter. However, no overall agreement exists on regional climatic changes such as warming or cooling or drought patterns, although the results do suggest an increase in the global precipitation rate by 3 to 11 percent with a doubling of the CO_2.[94(5-9)]

Temperature measurements over the past century are shown in Figure 51 (Jones and others, 1986[94(10)]; Oort and others, 1987[94(11)]), although pre-1900 temperature trends are controversial.

Figure 51: Global and Hemispheric Annual Mean Temperature Variations Since 1861[94]



Jones et al, 1986[94(10)]



Oort et al, 1987[94(11)]

Figure 51 has been interpreted as showing an increasing trend of 0.3° to 0.7°C depending on location. It also shows the dilemma that the world is facing on the question of global warming. Here we have two sets of workers portraying ostensibly the same information - the annual mean temperature variations over the past 130 years or so - and their graphs are entirely different. The only way in which we will get reliable information is for the most knowledgeable scientists in this field to agree on the basic criteria for measuring the Earth's temperature.

The sea level has been rising over this period, too, but several factors could be responsible for the change.

At a regional level in Europe, a warming trend is indicated by the retreat of valley glaciers.[94(12)]

These systems fit the general pattern forecast by climatic models, but are not necessarily causally linked to the increased concentration of greenhouse gases in the atmosphere. Hence, it is not certain how to quantify the effects of a further increase in the future.

We are left, therefore, with the vital question of defining what is normal to our climatic system, i.e. what has happened before? CO_2 concentration and global warming in the past do correlate. The difference between the CO_2 concentration now and that 100 years ago is similar to the difference between a glacial and an interglacial climate. Likewise, the sea level has changed before. Thus, the potential changes predicted for the next century are not new to the Earth. The big difference is time-span. The effects of the greenhouse gases accumulation are predicted to occur over 150 years, whereas such changes in the past occurred over much longer time periods.

Furthermore, the doubling of the CO_2 concentration in the Earth's atmosphere, which is being considered in the modeling experiments, is just a convenience for the modeler. No obvious reason exists as to why greenhouse gases emissions should stop increasing at that point. The inertia of the system means that warming, if it is fact, may well continue after the point at which emissions might be modified.

CO_2 emissions can be controlled by abatement (or prevention)

- by reducing overall demand for energy (conservation),
- by improving the efficiency of combustion cycles, and
- by substituting with fuels which produce less, or no, CO_2

and, to a lesser extent, by control

- by removal (disposal), and
- by reforestation and/or improved forest management.

Energy saving technologies were reviewed by Cheng et al[94(13)] in 1986.

Emissions of CO_2 from fossil fuels depend on their carbon content and heating value, as well as on how they are burned. The emission factors used generally[94(14,15)], kgC/GJ, are based on the gross heating value, i.e. the heat of combustion when all the product water condenses. They include:

- bituminous coal ..... 24.1 kgC/GJ
- crude oil ..... 19.9 kgC/GJ
- natural gas ..... 13.8 kgC/GJ

Thus, effectively, coal produces about 20 percent more CO_2 per unit of heat than does oil and 75 percent more than natural gas.

The emission factor for coal ranges generally from 23.2 to 25.4 kgC/GJ, although anthracites and semi-anthracites have higher values, up to 26.4. Thus, varying the type of coal used offers little opportunity to reduce CO_2 emissions.

CO_2 emissions from all fossil fuels can be reduced by developing more efficient utilization technologies. Take, for example, the power generation sector. Table XXXIII shows the efficiencies of currently operating, or demonstrated, technologies.

Table XXXIII: Power Generation Efficiencies[94]

Technology	Efficiency	
	%	gCE/kWh*
Conventional pulverized coal combustion, with flue gas desulfurization (PF+FGD)	35 - 38	325 - 335
Circulating fluidized bed combustion (CFBC)	35 - 38	325 - 335
Integrated gasification combined cycle (IGCC)[94(16,17)]	38 - 40	310 - 325
Pressurized fluidized bed combustion (PFBC)[94(16,17)]	38 - 40	310 - 325

* gCE = grams Carbon Equivalent

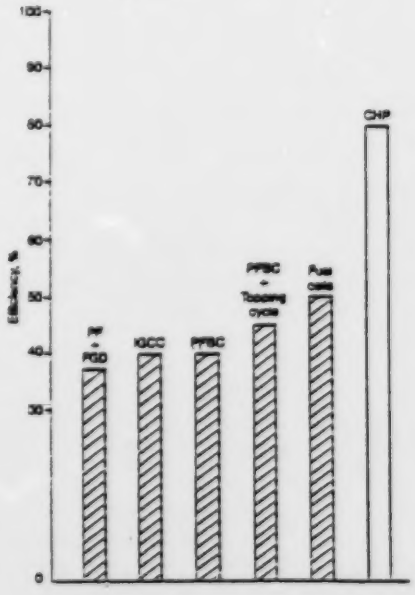
Another technology which has been demonstrated to a limited extent is the combined PFBC and topping cycle. The gases from the PFBC are heated by the addition of a topping gas from an associated gasification system to feed a high temperature gas turbine. This technology is being developed in the UK and in the USA; it promises to improve efficiency up to 45 percent. The increase in efficiency over PF+FGD represents a reduction in CO_2 emissions by 17 percent.[94(16)]

Efficiencies of 50 to 60 percent (245 to 205 gCE/kWh) are believed achievable with combined cycle methods and fuel cells.[94(17)]

Even with these advanced technologies, significant heat losses still exist. These can be exploited in combined heat and power systems for all power cycles (with a small reduction in electrical power) to achieve overall efficiencies exceeding 80 percent (150 gCE/kWh).

Figure 52 summarizes the potential for efficiency improvements in power cycles.[94(16,17)]

Figure 52: Efficiency of Power Cycles[94]



While the timing to commercialization of advanced power generation technologies is uncertain, it is theoretically possible to meet the Toronto target of a 20 percent reduction in CO_2 emissions. Delays in introducing and adopting these technologies, however, would extend the timing beyond the target year 2005.

The greatest effort on behalf of coal seems to be in the USA where the Department of Energy (DOE) has invested heavily in the research and development of clean coal technologies.[97] They believe the potential payoff in terms of energy and economic security and environmental protection to be extremely high.

The clean coal technologies comprise a wide range of technologies which can be used on their own, or in combination, for a variety of market applications. They include:[97]

- precombustion processes which can remove sulfur, ash and moisture from a variety of coals to lower transportation costs, improve boiler performance, and reduce pollution at user sites,

- advanced combustion processes which more efficiently, more economically, and with improved environmental performance, produce steam and/or electricity for a number of industrial, commercial, and electric utility applications,

- pollution control devices which should lower the cost of controlling sulfur dioxide, nitrogen oxide, and particulate matter from coal-burning facilities, both new and existing, while at the same time producing wastes that are easy to dispose of, regenerate, or market, and

- technologies that can convert coal to gaseous or liquid products which can substitute directly for natural gas and oil, even in railroad locomotives, trucks and automobiles.

Since 1981, the DOE has invested over two billion dollars in these clean coal technologies; state agencies and private industry have invested a similar amount. Over the next several years, the DOE intends to spend another two to three billion dollars, while other federal agencies, state agencies, and US industry are expected to invest nearly four billion dollars of their funds to support the advancement of these technologies.[97]

It behooves the Canadian (and international) coal industry to get involved in communicating the merits of clean coal technologies, in communicating the message that coal usage and environmental degradation are not, or need not be, synonymous, and in developing innovative approaches that solve problems in using coal.

Coal does not have a good public image, and politicians the world over are becoming increasingly sensitive to the public's growing concern about the environment.[98] The main environmental issues are three:

1. acid rain: coal-fired plants are perceived as a major source of acid-rain-causing emissions, and governments will inevitably set increasingly stringent standards for emissions contributing to acid rain,

2. NO_x emissions: recently, 15 countries signed a protocol to freeze NO_x emissions at the 1987 levels by 1994, which could have a serious impact on the coal industry if economic and effective NO_x reduction technology is not available, and

3. global warming: this issue is receiving much public attention, with many scientists predicting a global warming of 1° to 5°C within the next 50 years. Although this is a prediction and the evidence is not yet conclusive that the Earth's temperature will

change, the coal industry and its customers must take initiatives to deal with this issue.

The CO_2 emissions issue will take time to study and resolve; the sources of CO_2 are varied and numerous, including both natural and man-made. While technology exists to reduce acid-rain-causing emissions, and protocols have actually been signed to contain NO_x emissions and to ban CFC production, technological and economic solutions for CO_2 have yet to be developed. In the meantime, coal is in danger of becoming a scapegoat on this issue, even although it contributes <10 percent to the man-made emissions that could cause global warming.[98]

As the politicians become involved, more stringent environmental constraints may be expected on all industries. Governments of certain countries are already toying with the idea of a CO_2 tax.[99, 100] Taxation seems to be governments' way of dealing with many situations; innovative thinking must come from the industries involved.

The coal industry may be a particular target for constraint for two reasons.[98]

1. Coal is perceived, generally, as a major source of pollution.

2. The technology to deal with coal-related environmental problems is perceived to be unavailable, insufficiently ineffective, and/or too costly.

These perceptions may, or may not, reflect reality, but they exist and must be addressed. In doing so, the coal producers and coal consumers must resist the temptation to downplay the true environmental impact of coal.

Mr. M. Williams[98] suggests five initiatives that the Canadian coal industry should take to deal with the environmental concerns of the public.

1. The industry must strongly support coal R&D, specifically R&D into effective and cost-efficient clean coal technology. It will pay dividends in the future with more opportunities for the use of coal. Multiparty R&D ventures are encouraged because they lessen the individual financial burden and often provide more creative results through the pooling of knowledge.

2. The industry must increase public awareness of the importance of coal in meeting the world's energy needs and of what is being done to overcome real or perceived problems. The challenge will be to convince the public that clean coal technologies are possible, and can be both effective and cost efficient.

3. The industry must promote energy conservation in the context of using energy wisely. Conservation is one of the most effective and quickest ways to deal with many environmental issues simultaneously, including global warming.

4. The industry must promote public education, i.e. to inform the public on energy and the economy, and to champion environmental issues. The total environmental impact of the various energy resources should be compared objectively. The positive impact of the coal industry needs to be communicated, including its contribution to the economy and employment. Included in this initiative must be the education of young people.

5. The industry needs to continue taking a proactive role in government policy development. Close contact and relations must be maintained with key elected officials and bureaucrats, both federally and provincially, to ensure that the coal industry has a part in shaping new policies.

It behooves the coal-consuming industry to remain current on the issue of the "greenhouse effect"/global warming and to strongly collaborate in any initiative to promote the positive aspects of coal and have a part in shaping government policy, since their future well-being, perhaps even survival in this country, is also at stake. Time may be short; Ontario's Minister of Energy expected to release a policy paper (a "White" paper) on global warming by the end of 1990.[100] The government's discussion paper released earlier this year, 1990, notes that one of the government's options is a tax on CO_2 emissions. This type of tax could be devastating to coal-based industries, and to the customers of coal-based electric generating units. Since then, the Ontario government has changed - to a government that is likely to be even more militant with respect to environmental issues.

IMPACT

The impact of the emerging technologies will be felt by most of the members of the Consortium for the Strategic Study of Future Ironmaking Processes.

The integrated steel plants face the major problem of aging coke ovens; the minimill steel plants face a number of problems, including feedstock which will allow them to enter the higher-value steel product market, possibly even including flat-rolled. Strategic decisions will be needed concerning the future technologies to be employed at these plants. Some of these decisions will undoubtedly be influenced by pollution control legislation. The decisions to be made could well affect other industries such as coal, electric power, natural gas, iron ore, scrap, and slag.

The Canadian integrated steel industry, for the most part, has adopted new technology early and this has been one of the major keys to its success over the years. However, this industry, in concert with its counterparts in other industrialized countries, is facing the dilemmas of aging equipment, high and escalating costs of replacement equipment, and a seemingly ever-increasing price/profit squeeze. Market competition from low-cost areas of the world is fierce and steelmaking capacity in some of these countries continues to expand. At home, demands by provincial governments in environmental control and other areas escalate the cost of production in a steel over-supply situation which militates against raising steel prices.

Blast furnace ironmaking will continue to be the dominant technology employed by the steel industry well into the next century. The blast furnace's demise has been forecasted several times but technological enhancements have always brought it back stronger than ever. Today, this process is in a state of evolution once more, an evolution primarily to make it more independent of coke and, hence, of coke ovens.

The two basic problems with coke ovens are the capital cost of additional or replacement facilities and the environmental issues involved. But coke is vital to the operation of the blast furnace!

As of the beginning of 1989, the effective annual capacity of the cokemaking facilities of the Western world is estimated to total over 205 million tonnes.[101] This tonnage represents a capacity decrease of 13.6 million tonnes (6%) since 1985 and one of 46.6 million tonnes (18%) since 1982. These decreases would have been greater had facilities closures not been offset, partially, by new facilities coming on stream. From 1984 to the beginning of 1989, nearly 16 million tonnes of new cokemaking capacity has been commissioned, notably in Brazil, India, and Korea, representing about eight percent of the total cokemaking capacity of the Western world. The Federal Republic of Germany is the only industrialized country in which a major coking industry modernization program has been implemented.

The overall age profile of the Western world's coke ovens and coking capacity is shown in Table XXXIV.

Table XXXIV: Age Profiles - Coke Ovens and Coking Capacity*

	Age Profile, Percent					Total
	<5 Yr	5-15 Yr	16-25 Yr	26-30 Yr	>30 Yr	
Ovens	7.8	31.2	33.4	8.7	18.7	28 514
Capacity	10.4	36.5	35.9	6.2	11.0	205.706 x 10^6 t/yr

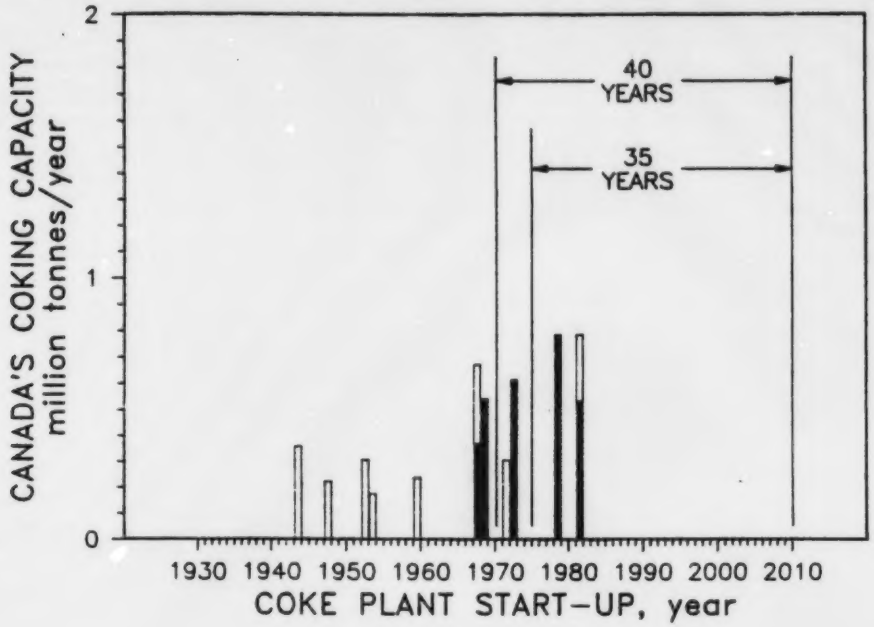
* as of 89 01 01 (IISI data[101])

The overall trend in cokemaking capacity continues to decline until 1990, after which it increases slightly. Ensidesa in Spain have planned a large rebuilding program for the 1990s: Gijon batteries No. 1 and No. 2 are scheduled to be rebuilt between 1993 and 1996, Aviles batteries No. 5, No. 6, and No. 7 during the period 1990 to 1992, and Aviles batteries No. 1, No. 2, No. 3, and No. 4 during 1997 to 1999. In Brazil, Aco Minas Gerais, Companhia Siderurgia de Tubarao, and Companhia Siderurgia Nacional all plan to open new coking facilities. In Chile, the aging coke ovens at Huachipato are to be closed in December 1990, and be replaced by new facilities due to come on stream at Huachipato in September 1990. New capacity at Bowen and Port Kembla in Australia will more than compensate for the scheduled closure of Port Kembla's 3A battery. The Steel Authority of India will open a new battery at the Durgapur steel plant in 1991. In the Republic of Korea, the No. 3 coke oven battery at Kwangyang is also due to come on stream in 1991. China Steel in Taiwan (ROC) is expected to start up new batteries No. 7 and No. 8 sometime between 1990 and 1995.

The production of coke is linked closely to the production of blast furnace iron. However, while the production of pig iron in the Western world is at a similar level to what it was some 10 years or so ago, the Western world's production of coke has fallen by about nine percent. Since 1975, the production of coke in North America has dropped by nearly 45 percent and that in Europe by over 30 percent. Western Europe now accounts for 33 percent of Western world coke production, down from 40 percent in 1975; North America now accounts for 18 percent, down considerably from its 27 percent share in 1975. In contrast, coke production in Asia and Latin America (about 84 million tonnes annually) is generally increasing, with a combined share, now, of 44 percent compared to 29 percent in 1975.

The overall trends noted above are expected to continue. In Canada, Japan, the USA, and Western Europe, steel production based on blast furnace ironmaking is expected to remain essentially constant for the foreseeable future, but with decreasing reliance on coke. Old batteries will be shut down, not necessarily because they cannot continue to produce coke but because the cost of retrofitting adequate pollution control equipment to meet current and proposed government environmental standards renders their continued operation uneconomical. By and large, such batteries will not be replaced if a viable alternative can be found. The magnitude of the problem may be appreciated, perhaps, from a study of Figures 53 to 56 which show current coking capacity (89 01 01) according to coke oven start-up year for Canada, Japan, the USA, and Western Europe, respectively.

Figure 53: Canada's Coking Capacity by Start-Up Year (IISI Data[101])



Note: the solid black histogram elements in Figures 53 to 56 represent tall ovens 5 m or more in height.

Figure 54: Japan's Coking Capacity by Start-Up Year (IISI Data[101])

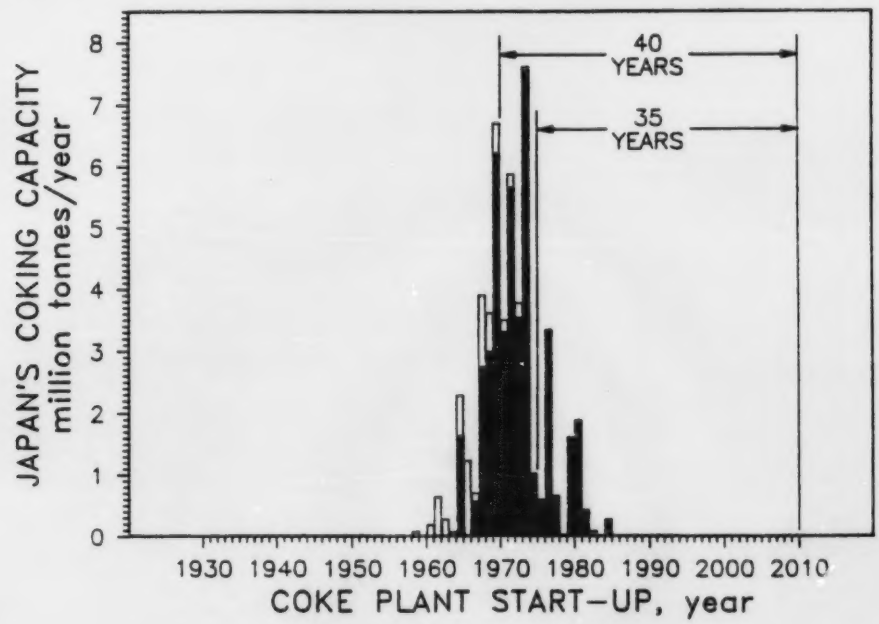


Figure 55: The USA's Coking Capacity by Start-Up Year (IISI Data[101])

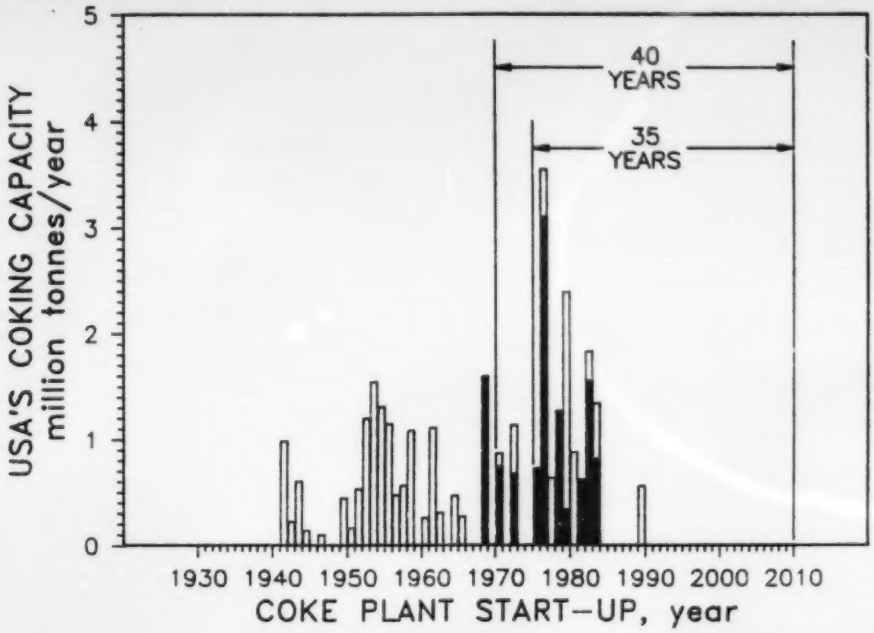
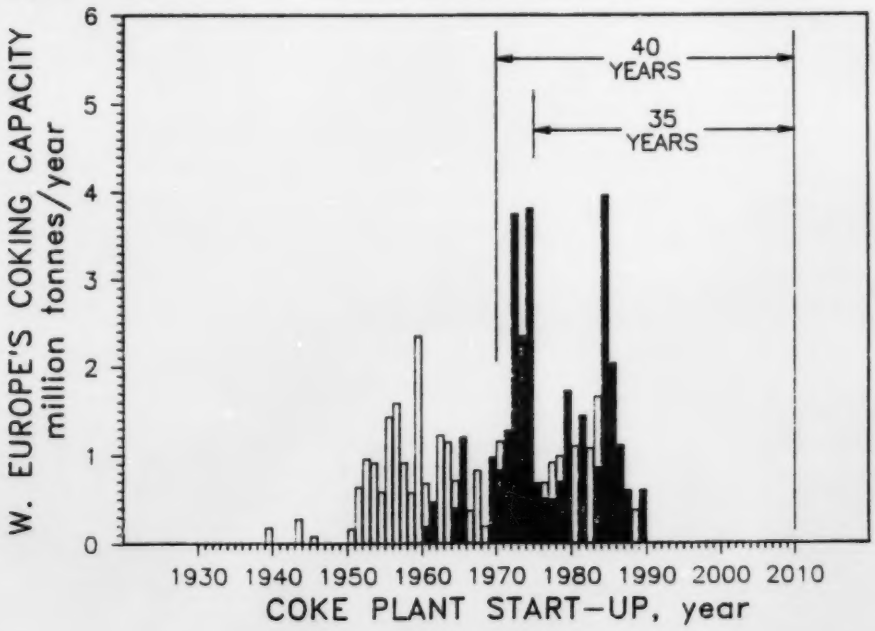


Figure 56: Western Europe's Coking Capacity by Start-Up Year (IISI Data[101])



Figures no. 53 to no. 56 may be summarized as in Table XXXV to provide some insight into the situation being faced by the steel companies in these four areas of the world. It shows the coke capacity constructed in various time periods.

Table XXXV: Coking Capacity Age Summary

Region	Annual Capacity Installed, 10^6 tonnes (%)			Total
	From 1980	From 1970	To 1970	
Canada	1.123 (21.0)	2.825 (53.0)	2.508 (47.0)	5.333
Japan	2.661 (5.3)	30.680 (60.9)	19.669 (39.1)	50.349
USA	5.260 (17.3)	15.863 (52.3)	14.466 (47.7)	30.329
Western Europe	17.315 (28.6)	40.699 (67.1)	19.935 (32.9)	60.634

By the year 2010, 82.0 percent of today's coking capacity will be older than 30 years and, of that, almost one-half will be older than 40 years, as may be seen in Table XXXVI.

Table XXXVI: Aging of Coke Ovens

Region	Coking Capacity, 10^6 tonnes (%)				
	Age by 2000, years		Age by 2010, years		
	>30	>40	>30	>35	>40
Canada	2.508 (47.0)	1.297 (24.3)	4.210 (89.0)	3.426 (64.2)	2.508 (47.0)
Japan	19.669 (39.1)	0.073 (0.14)	47.668 (94.7)	41.458 (82.3)	19.669 (39.1)
USA	14.466 (47.7)	10.440 (34.4)	25.069 (82.7)	16.476 (54.3)	14.466 (47.7)
Western Europe	19.935 (32.9)	10.655 (17.6)	43.319 (71.4) 120.266 (82.0)	36.023 (59.4) 97.383 (66.4)	19.935 (32.9) 56.578 (38.6)

The coking capacity available, from current batteries, in the year 2010 is shown in Table XXXVII.

Table XXXVII: Coking Capacity in 2010 Based on Current Batteries

Region	Coking Capacity in 2010, 10^6 tonnes, if Coke Oven Life is			Current Capacity 10^6 t
	30 Years	35 Years	40 Years	
Canada	1.132	1.907	2.825	5.333
Japan	2.681	8.891	30.680	50.349
USA	4.695	13.288	15.298	30.329
Western Europe	16.945	24.241	40.329	60.634

Apart from the decline in the overall production capacity of the coking industry of the Western world, another consideration is the general physical condition of the cokemaking facilities. The efficiency of a coke oven can decrease with age and, although the maximum useful life is generally accepted to

be approximately 30 years (35 years, by some Japanese estimates), its productivity may fall off significantly before this time and almost certainly beyond this time[101] as companies seek to prolong its life and, hence, the expenditure to replace it. Some batteries today are older than 40 years; maximum life for today's batteries may be closer to 35 years - depending on how they are operated, maintained, etc, as well as on their design.

Thus, as has long been recognized, the industrialized world faces a crisis in blast furnace coke supply by 2010 and, indeed, even well before then.

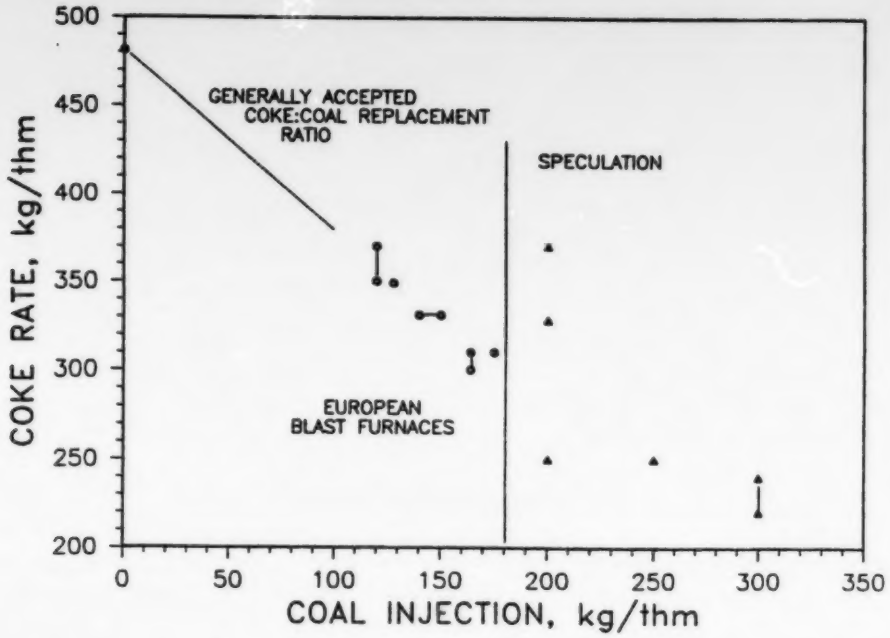
Actually, the greatest threat to the blast furnace process may well be legislative, not technological - legislation which will affect the economical production of coke. Such a situation, however, could provide an opportunity for the steel plants to shed what has often been a troublesome operation and to purchase coke as a commodity, just as they do pellets - provided they can make the necessary adjustments to in-plant energy supply, etc. Such a situation would also be an opportunity for some enterprising groups or companies to develop a new strategic business in the right locations. The possibilities are many; for example, the collaboration of coal companies and electric utility companies to produce coke and electricity from non-recovery coke ovens, just to mention one.

In the meantime, the major strategy of the integrated steel companies to overcome the looming coke shortage is the injection of coal through the tuyeres of the blast furnace at ever-increasing rates. By substituting directly for a portion of the coke charged to the blast furnace, the injected coal can be used to:

- offset coking capacity lost through the closure of coke batteries, and/or
- allow operating batteries to be slowed down, thereby prolonging their life.

European steel companies are the leaders in coal injection at this time, especially British Steel Corporation, Hoogovens, and Thyssen Stahl, where the maximum coal injection rate is being pushed ever higher on operating blast furnaces. While many blast furnaces are far from it, the general trend in coal injection in Europe is to strive for a coal injection rate of about 160 kg/thm; the next aim level is injection at the 200 kg/thm rate. Figure 57 shows the injection levels that have been achieved to date; those below 150 kg/thm are "normal" operating levels while those between 150 kg/thm and 200 kg/thm are lengthy test periods and those above 200 kg/thm are essentially speculation (based on experience, calculations, etc).

Figure 57: Coal Injection Rates - Europe[102]



Many blast furnaces have not yet adopted coal injection technology and some of those that have find themselves in an under-capacity situation, i.e. they need more grinding/drying capability or greater delivery capacity. Corporate planning increasingly includes coal injection and/or increased injection capability.

In looking at European blast furnace iron production as a whole, the overall coal injection rate is just over 29 kg/thm. The situation in Japan is similar at an overall injection rate of just under 29 kg/thm with, proportionately, more blast furnaces injecting coal but at lower rates than in Europe. No coal injection at all is practiced in Canada and the level employed in the USA, against the total hot metal production there, also approaches zero. All of this seems to suggest a rather large degree of industry-wide maneuverability in planning around obsolete or soon-to-be-obsolete coking capacity.

Figure 57, starting at a coke rate of 481 kg/thm (Schwelgern no. 1 blast furnace, Thyssen Stahl)[103], shows the generally accepted coke replacement line, i.e. coke:coal :: 1:1 up to an injection rate of 100 kg/thm. However, the data obtained from operating blast furnaces line up with this line, indicating that, depending on the operating practices employed, the coke replacement ratio does not have to deteriorate at injection rates above 100 kg/thm. Extending the coke replacement line, therefore, indicates that the coke rate with 160 kg/thm injected coal would be about 320 kg/thm and with 200 kg/thm, by minor extrapolation, it would be about 280 kg/thm.

With no change in pig iron production, the coke requirements for the various areas under consideration would be as indicated in Table XXXVIII.

Table XXXVIII: Regional Coke Requirements According to Coal Rate

Region	Coke Requirements, 10^6 tonnes/year, at Coal Injection Rate of	
	160 kg/thm	200 kg/thm
Canada	3.357	2.937
Japan	25.663	22.455
USA	16.139	14.123
Western Europe	32.383	28.335

Thus, the coking capacity which will have to be replaced, with either new or rebuilt batteries, to sustain current blast furnace ironmaking production in these four regions to the year 2010 is rather substantial, as shown in Table XXXIX.

Table XXXIX: Additional Coking Capacity Required to 2010

Region	Coke to Sustain Pig Iron Production, 10^6 t/yr,		
	Available*	Additional Required for Coke Rate of	
		160 kg/thm	200 kg/thm
Canada	1.907	1.450	1.030
Japan	8.891	16.772	13.564
USA	13.288	2.851	0.835
Western Europe	24.241	8.142	0.094

* assuming 35-year life of present capacity

Proportionately more new or rebuilt coking capacity will be required if the projected coal injection rates do not come into widespread use. Furthermore, Table XXXIX does not take into account the additional coking capacity which will be required to sustain pig iron production at its current level beyond the year 2010.

The injection coal needed to minimize the additional coke requirements is shown for each region in Table XL.

Table XL: Regional Injection Coal Requirements

Region	Coal Requirements, 10^6 tonnes/year, at Coal Injection Rate of	
	160 kg/thm	200 kg/thm
Canada	1.678	2.098
Japan	12.832	16.039
USA	8.078	10.087
Western Europe	16.191	20.239

Practically every type of coal has been injected successfully somewhere. The specifications for injection coals vary from plant to plant but, in discussing this aspect of coal injection with those using this practice, the most important specification was found to be low price. Thus, the more lucrative market for millions of tonnes of coking coal, supplied by a select few companies which can match the rigid specifications, will be replaced by a market for millions of tonnes of injection coal which can be provided by many more producers. More details on injection coal specifications are given below:

- lower ash (6 to 8%) is preferred to higher ash (although 11% is acceptable in some plants),
- lower sulfur is preferred, i.e. no increase in input sulfur/thm,
- coking or noncoking coals may be injected,
- semianthracite (11% VM) to medium volatile matter coals; actual specifications range from low volatile (=21%) to high volatile matter coals (=35%),*
- grindability (Hardgrove Index, HI) is specified in some plants at HI <50, but this is not in general use,
- grind varies from granular (0.7 to 1.7 mm) to pulverized (80% <0.075 to 0.090 mm),**
- all injection coal must be dried to no more than one percent H_2O.

When it comes to injection coal specifications, probably the best rule-of-thumb is to inject coal of the same quality as that of the coke being charged to the blast furnace, i.e. same ash, same sulfur content.

Once an injection rate of around 80 to 100 kg/thm has been reached, the major barrier to increasing the coal injection rate is combustion of the coal at the tuyeres. Oxygen enrichment of the hot blast is the technique most commonly used to overcome this barrier. (The major exception was on Thyssen's Hamborn no. 4 blast furnace which was reported to have operated smoothly during a test period in 1986 at an injection rate of 150 kg/thm without oxygen enrichment.[108]) There are actually two reasons why oxygen enrichment is used:

- increased productivity, and
- increased combustion capability at the tuyeres, i.e. the capability to increase the rate of hydrocarbon injection (natural gas, fuel oil, tar, coal, etc).

This duality of purpose explains, in large measure, the wide variation of oxygen enrichment levels being used with coal injection today. Burgess et al[109] have developed the relationships among coal injection rates, coke rates, oxygen enrichment, fuel rates, specific wind rates, and specific oxygen rates (Figure 58).

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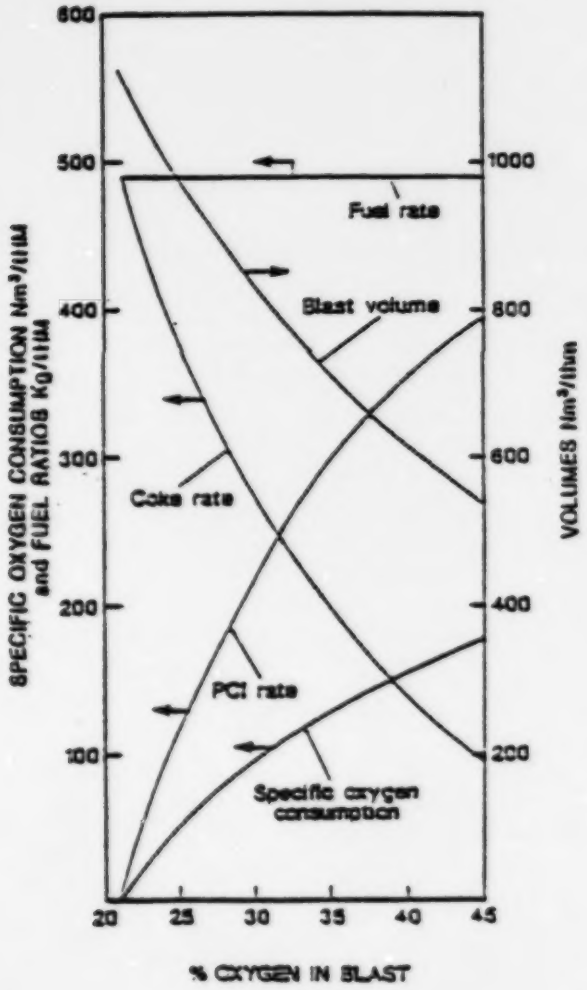
* No real agreement exists. Measurements in a commercial blast furnace revealed that the combustibility of the coal improves with increasing volatile matter content and decreasing fluidity. The conclusion was drawn that high volatile coal with no fluidity is the most preferable coal for pulverized coal injection.[104] On the other hand, a regression analysis of data obtained from 52 operating blast furnaces indicates that low volatile coal is desirable for maximum coal injection rate, replacement ratio, and productivity.[105] Others are also studying coal combustion related to coal injection.[106, 107]

** The granular coal injected at Scunthorpe is now much finer than the grind for coke ovens. On the other hand, some of the plants injecting pulverized coal have shifted to a slightly coarser grind to increase the grinding capacity of the system to enable higher injection rates to be attained, with no apparent deterioration in the blast furnace operation.

Figure 58: Combustion Input Relationships[109]



From Figure 58, coal injection rates of 160 kg/thm and 200 kg/thm will require oxygen enrichment of the hot blast to 26.9 percent and 28.8 percent, respectively. What this means to the four industrialized areas under consideration may be seen in Table XLI.

Table XLI: Regional Oxygen Requirements*

Region	Oxygen Requirements, 10^6 Nm^3/year (10^6 t/yr), at Coal Injection Rate of	
	160 kg/thm	200 kg/thm
Canada	713 (1.02)	881 (1.26)
Japan	5454 (7.79)	6736 (9.62)
USA	3433 (4.90)	4237 (6.05)
Western Europe	6881 (9.83)	8500 (12.14)

* including already existing enrichment oxygen capacity

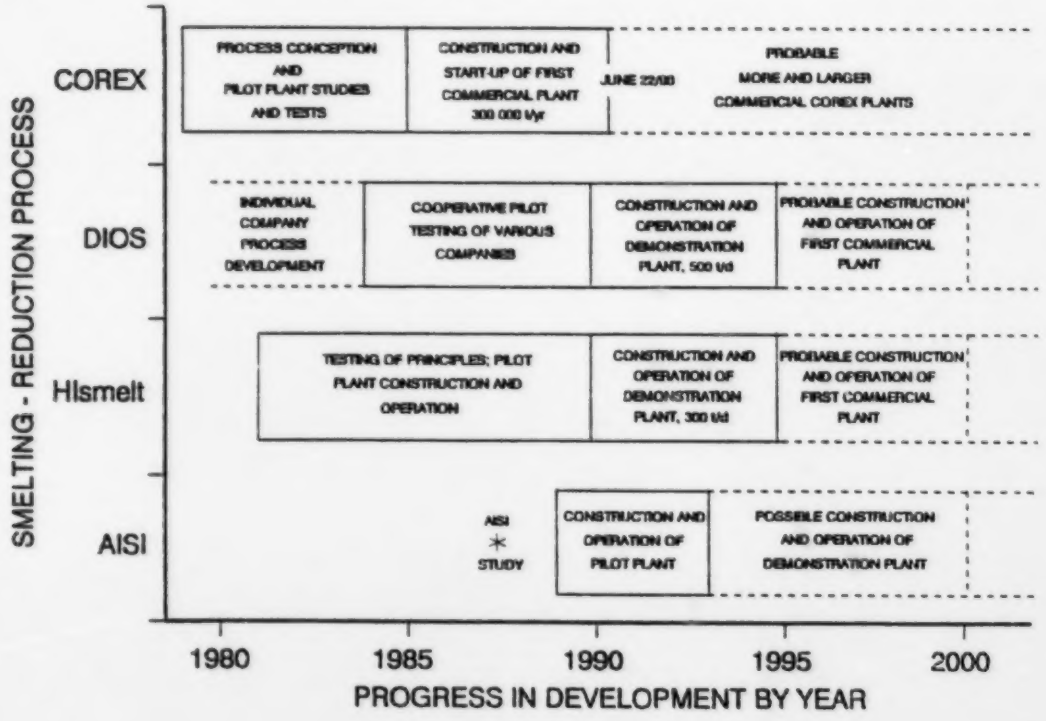
Oxygen enrichment levels of 26.9 percent and 28.8 percent for coal injection rates of 160 and 200 kg/thm, respectively, may actually be a little on the high side, based on the results of blast furnace trials. Nevertheless, they are reasonable.

Other approaches have been, and are being, tried to decrease the dependency of the blast furnace on coke. These include:

- plasma superheating of the hot blast, which has met with some success in France; however, this technology requires an abundance of inexpensive electricity and, hence, it is not likely to enjoy widespread application,
- the injection of ore fines, preferably partially reduced, along with coal injection, which is still in the early stages of development,
- combined blast, the injection of natural gas at high injection rates with high levels of oxygen enrichment of the hot blast; however, this technology requires an abundance of inexpensive natural gas and is more limited than coal/oxygen injection in its ability to replace coke, and
- smelting-reduction, the direct smelting of iron ore with coal, doing away with the coke ovens, the blast furnace and, in some of these processes, ore agglomeration.

Despite the declared Japanese intention to replace blast furnace ironmaking capacity with their DIOS process, the smelting-reduction processes will make little, if any, inroad into pig iron production by blast furnaces - certainly not in this decade and most likely not in the next. Only one, COREX, has reached the small commercial stage; the other contenders are only now constructing demonstration plants. The situation with the smelting-reduction processes is illustrated in Figure 59.

Figure 59: Smelting-Reduction Processes Update


SMELTING - REDUCTION PROCESS
COREX
DIOS
Hismelt
AISI
PROCESS CONCEPTION AND PILOT PLANT STUDIES AND TESTS
CONSTRUCTION AND START-UP OF FIRST COMMERCIAL PLANT 300 000 t/yr
JUNE 22/00
PROBABLE MORE AND LARGER COMMERCIAL COREX PLANTS
INDIVIDUAL COMPANY PROCESS DEVELOPMENT
COOPERATIVE PILOT TESTING OF VARIOUS COMPANIES
CONSTRUCTION AND OPERATION OF DEMONSTRATION PLANT, 500 t/d
PROBABLE CONSTRUCTION AND OPERATION OF FIRST COMMERCIAL PLANT
TESTING OF PRINCIPLES; PILOT PLANT CONSTRUCTION AND OPERATION
CONSTRUCTION AND OPERATION OF DEMONSTRATION PLANT, 300 t/d
PROBABLE CONSTRUCTION AND OPERATION OF FIRST COMMERCIAL PLANT
AISI
STUDY
CONSTRUCTION AND OPERATION OF PILOT PLANT
POSSIBLE CONSTRUCTION AND OPERATION OF DEMONSTRATION PLANT
1980
1985
1990
1995
2000
PROGRESS IN DEVELOPMENT BY YEAR

The COREX process, although at the commercial stage in the Pretoria Works of ISCOR, in South Africa, is still being debugged. It is expected to be about two years before another COREX plant will be built.[2] The DIOS and HIsmelt processes should both have completed their demonstration plant trials by the middle of this decade and have a reasonably firm idea of the capital and operating costs for a commercial plant. It would be most surprising if a commercial-sized plant of either of these processes were to be built and debugged by the end of this century. The AISI process, if it proves to be successful at the pilot stage, will still have to proceed through the demonstration stage, which will take it almost to the year 2000, about five years behind DIOS and HIsmelt. Thus, even if these processes are highly successful, any impact they might have on the blast furnace as the primary vehicle to produce tonnage iron will not be felt until after the year 2010, perhaps long after. Their impact is more likely to be seen first on those minimills which want to enter the flat-rolled products market.

Minimill steel plants, collectively, have become a major force in the steel business. Electric arc furnace steelmaking, the basis of minimill operations, has increased its share of world crude steel production from 11 percent in 1960 to 27 percent in 1988. Its share in Canada is about 30 percent although, in Ontario, where all the integrated steel plants are located, its share is slightly over 15 percent.

Essentially, electric arc furnace steelmaking is a relatively low capital cost, low labor cost operation using an expensive form of energy to process what has most often been an inexpensive metallurgical feedstock. However, it has traditionally had a limited product range.

Scrap-based EAF steelmaking is increasingly under pressure for metallurgical reasons. Competition in the marketplace keeps demanding ever-higher levels of quality. The production of steels at the higher end of the quality scale has been hampered by the presence of harmful residual elements in the steel scrap feedstock.

The two ways that have been, and are increasingly being, used to overcome this problem are scrap processing to lower the level of harmful residual elements, e.g. Cu, Sn, etc, in the scrap charge and/or dilution with direct reduced iron (DRI), hot briquetted iron (HBI), pig iron, etc. (Scrap processing can also entail the sorting of scrap so as to concentrate higher-cost alloying elements, e.g. Cb, Mn, Mo, V, etc, required for certain product grades, thereby effecting a saving in alloy purchases.)

In principle, scrap merchants have no reason to refrain from introducing statistical process control to satisfy the requirements of their customers for scrap quality. In practice, according to Aylen[110], the complexity of the quality information seems to require scrap processing in-house. Because of the reluctance of scrap dealers to guarantee residual levels as part of a market transaction, EAF steelmakers are tending towards backward integration into scrap processing so as to take control over feedstock quality for themselves. Scrap selection and upgrading appear to be inevitable but, going by European experience, could raise the cost of scrap by up to US$ 8 to 10 a tonne (however, with some offsetting gains in yield and metals recovery).

DRI is used at a number of EAF steelmaking plants, e.g. Hamburger Stahlwerke, Georgetown Steel, Sidbec-Dosco, etc, to produce higher quality end products. However, the consensus is that no more DRI-producing units will be built in Canada or in the other industrialized nations. The cost of natural gas, the source of the reducing gases, prohibits such installations from being economically viable. Thus, any increase in DRI utilization in these countries will rely on merchant DRI, probably in the form of hot briquetted iron.

As the proportion of coal as an energy source goes up and the reserves of oil and natural gas come down worldwide, the growth of coal-based direct reduction processes should become more marked.[76] On the other hand, some consideration has been given to the gasification of coal to replace the natural gas feed to gas-based processes as the price of natural gas increases or its availability decreases - to this point a too costly alternative. Some of the newly emerging smelting reduction

processes may hold the key to utilizing gasified coal effectively, at least those which have separated the reduction function from the melting/smelting function.

Taking the COREX process as an example, since it is the one which has reached the commercial stage, the melter-gasifier devolatilizes (cokes) the charged coal particles and cracks the hydrocarbons into CO and H_2, except for a minor percentage of methane (CH_4). The hot, highly reducing gases exiting the melter-gasifier are dedusted, temperature-adjusted by blending with cool gases of the same composition, and injected into the Midrex-type reduction shaft to reduce the iron ore prior to its being fed hot into the melter-gasifier. The end product hot metal is much superior to DRI in that it is virtually the same as blast furnace hot metal; the gangue has been separated from the iron by melting and enters the slag which has desulfurizing capability, the carbon content allows it the flexibility to be used as a major charge component in either a BOF or in an EAF, and the hot metal produced can be charged to the steelmaking furnace in the molten state using well-known handling techniques, with obvious energy benefits, or at remote installations it can be pigged or granulated for trouble-free shipment, both of these processes being well-known. Utilization of the hot metal in an EAF would require oxygen injection for carbon removal, but the benefits would be faster heats, lower consumption of electrodes and electricity, and flexibility in producing steels over a wide range of quality levels, i.e. freedom from the restriction imposed by undesirable residuals arising from the steel scrap feedstock.

What has been said of the EAF process and, by extension, the K-ES process, regarding the utilization of the output from a smelting-reduction process such as COREX, also holds true generally for the energy optimizing furnace (EOF). In this case, the COREX output would have to be charged molten or as iron "pigs", since other forms, e.g. granulated iron, would have too small a particle size for it to be processed through the preheating unit as is normally done with the entire solid metallic charge (usually steel scrap).

Steel Industry representatives predict that the growth in steel consumption in Canada will be virtually flat, with the most common prediction being one percent a year. While the probability may be low, scrap-based EAFs could be producing about 25 percent of the steel in Ontario within the next 10 years or so, up from the current level of 15 percent. This significant increase would occur if an integrated steel producer were to shut down blast furnace and BOF capacity along with obsolete coke ovens and replace them with equivalent EAF capacity. This alternative is intriguing because its cost may be no higher than to replace the coke oven battery alone - although producing steel to flat-rolled product specifications would likely be more difficult.

Scrap availability appears to be sufficient to support such an increase in EAF steelmaking which, along with higher scrap usage in the BOF, via post combustion, and lower scrap generation through continuous casting, would raise scrap consumption in Canada to about 5.5 million tonnes a year from 4 million by approximately the year 2000.

The scrap and steel industries will continue to face mounting scrap processing problems resulting from environmental concerns. Increasing quantities of "fluff" will be produced as automobile shredders receive auto hulks containing increasing quantities of nonferrous materials, heavy metals, and some hazardous materials. The concept of design for recycle will take on some considerable importance.

Reesor et al[69] have estimated a potential increase of 230 MW in electric power usage in Ontario in EAFs and ladle furnaces by about the year 2000. This estimate allows about 115 MW for four new ladle furnaces and larger transformers for two existing EAFs. It also allows about 115 MW for two EAFs to replace existing steelmaking capacity should blast furnace and BOF at one plant be shut down along with aged coke ovens.

The situation described above is certainly possible, but it could be altered drastically by technologies emerging on the scene, particularly the COREX, K-ES, and EOF processes.

The COREX Process

The COREX process, assuming it proves its viability at ISCOR, which it seems to be doing, may fit nicely into an existing integrated steel plant where a blast furnace has been torn down. It is possible that some of the ancillaries of the late blast furnace could be utilized to minimize the capital cost, e.g. the casthouse, gas cleaning and distribution systems, highline, charging system, and hot metal transportation. The steelmaking facilities would all be in place. Major advantages of this route to replacement capacity instead of EAF steelmaking include:

- ability to continue to produce all the high quality grades that need to start with a virgin iron base, i.e. no problems with residuals as in an all-scrap process,
- the nitrogen content of COREX hot metal is low, 0.002 to 0.003 percent, and remains at this level during steelmaking,[7]
- minimal process changes, i.e. produce hot metal to refine to steel in a BOF,
- gases generated by the process would be available as in-plant fuel, as was the blast furnace gas previously,
- no large perturbation of the scrap market, as there would be with a major new EAF facility seeking quality scrap with residuals levels low enough to be able to produce the same grades as previously via the blast furnace/BOF,
- no major increase in electricity demand, and
- no need to deal with the disposal of EAF dust which is becoming a serious environmental concern.

In this case, then, the electric power increase in Ontario by about the year 2000 for added EAF steelmaking capacity and ladle furnaces would drop to around 115 MW. On the other hand, the oxygen demand would increase markedly, by as much as 2000 to 2100 tonnes a day. The production of this quantity of oxygen would certainly require additional electricity but, possibly, sufficient off-gases might be siphoned off for combustion to generate the electricity required to produce the oxygen.

The K-ES Process

The major advantage of the K-ES process would be the saving in electric power required for a given production of steel through the substantial substitution of a primary energy source, coal, for electricity.

Potential advantages would be the following:

- lower electricity requirements, by 16 to 20 percent,
- higher productivity, by up to 50 percent, based on results reported to date, and
- built-in ability to recycle the furnace dust until the zinc content concentrates to such a level that it can be removed from the system and sold to a zinc producer.

Potential disadvantages would be the following:

- the same problems as the EAF in procuring sufficient high quality scrap at reasonable prices to continue to produce the same range of quality steel products,
- potential problems with sulfur from the coal,

- oxygen increase of 25 to 80 percent,
- natural gas consumption of 6.3 Nm^3/tonne liquid steel (or equivalent shrouding gas),
- coke/coal consumption of up to 25 to 30 kg/tls, depending on the weight of cold pig iron in the charge, and
- air quality problems; without a "dog-house", experience has shown that the atmosphere surrounding the EAF deteriorates when the furnace is converted to K-ES.

The EOF Process

The major advantages of the EOF process would be the following:

- no electricity is required directly in this process (as it is, for example, in the EAF),
- no electrode costs,
- it can be operated over a wide range of scrap:hot metal ratios, even up to 100 percent scrap,
- the quality of the steel produced is stated to be comparable to that produced in a Q-BOP, although with increasing scrap ratios, especially as 100 percent is approached, quality probably does begin to suffer from increasing residuals unless the scrap quality is rigidly controlled,
- energy efficiency via the built-in scrap preheater and the much lower volume of waste gas to clean (about 33 percent of that of an equivalent EAF shop), and
- smaller gas cleaning units.

The major disadvantages would be the following:

- coal consumption of up to 120 kg/t steel (100 percent scrap case) if anthracite or coke breeze is used; coal consumption increases as higher volatile matter coals are used,
- oxygen consumption of up to 135 Nm^3/t steel (100 percent scrap case),
- the same problems as the EAF in procuring sufficient high quality scrap to produce the full range of quality steel products (100 percent scrap case), and
- potential sulfur problems from the coal.

These three emerging technologies provide considerable flexibility in developing strategies to replace aging facilities or to enhance existing facilities. They have all reached the commercial stage. Admittedly, their use is not yet widespread and they may still need some fine-tuning. But, they are far enough advanced that their respective marketers should be able to estimate their capital cost, their operating cost, and their applicability to a specific situation with a high degree of accuracy.

With these three processes, the integrated steel producers have more possibilities in replacing coke ovens, blast furnace ironmaking, and BOF steelmaking, or selected portions thereof, and the minimills have options that will allow them to improve their operations and/or enter further the quality steel market, even the quality flat-rolled products market. The injection of coal into the BOF to increase the scrap:hot metal ratio is unlikely to enjoy widespread application, especially because of its adverse effect in lengthening the heat time.

All of these processes are carbon-based, as is the blast furnace. All will emit CO_2 into the atmosphere. Table XLII summarizes the CO_2 emissions released to produce hot metal and steel by the various processes discussed in this report.

Table XLII: Carbon Dioxide Emissions

Process	CO_2 Emissions		
	Ironmaking Process kg/thm	Steelmaking Process kg/tls	Total to Liquid Steel kg/tls
COREX			
a) with export gas	2455	[235]	2430
b) without export gas	1418	[235]	1500
Hismelt			
a) without prereduction	1862	[235]	1900
b) with prereduction	1876	[235]	1910
DIOS (with export gas)	2416	[235]	2390
AISI (with export gas)	2629	[6]	2640
BLAST FURNACE (with export gas)			
a) all coke	1996	[235]	2020
b) 50 kg NG/thm	1923	[235]	1950
c) 100 kg coal/thm	1974	[235]	2000
d) 150 kg NG/thm, ~35% oxygen	1793	[235]	1840
e) 200 kg coal/thm, <30% oxygen	1837	[235]	1880
BOF (80% hot metal)	[1950]	235	1980
KMS			
a) 40% scrap, 60% hot metal	[1950]	360	1640
b) 52% scrap, 48% hot metal	[1950]	546	1540
KS (100% scrap)	0	1193	1190
EAF	0	116	120
K-ES	0	169	170
EOF			
a) 50% scrap, 50% hot metal	[1950]	208	1300
b) 100% scrap	0	422	420

The values presented in Table XLII must be approached with considerable caution. They are included only as order-of-magnitude information and are not to be viewed as being absolute, since they reflect a mix of estimates and firm data, and even the firm data represent only one set of operating conditions (of which the permutations and combinations are extremely numerous). With this qualification, the CO_2 emissions shown in Table XLII are based on the following:

- total coal in - assuming all of its carbon is burned to CO_2 at some point, even if not directly in the process itself,
- the CO_2 from flux stone calcination,
- the carbon from auxiliary fuels such as natural gas and fuel oil, and
- the carbon required to produce the necessary electricity - either process electricity (EAF) or electricity required to produce oxygen - based on 20 percent of Ontario's electricity being thermally generated at 37 percent efficiency.

The emission of CO_2 is a fact of life in the production of tonnage iron and steel, especially from primary raw materials. While hydrogen is also an excellent reductant, with (environmentally friendly) water as the by-product of the reaction, it just cannot compete with carbon on the basis of cost. Thus, if Canada is to maintain a viable, i.e. cost competitive, steel industry, an industry of strategic importance to the nation, the production of tonnage iron must continue to be based on carbon reduction, which essentially means coal and coke.

The steel producers, for their part, as does every other user of coal, have the responsibility to minimize CO_2 emissions because of their potential to contribute to global warming. Minimization of CO_2 emissions can be effected in two ways:

1. maximum efficiency of operation, and
2. substitution of natural gas, with its substantial hydrogen content, wherever it is viable to do so - both technologically and economically.

If the coal users do not react voluntarily, and/or are not seen to react, they run the risk of government intervention which could seriously hamper their operations and/or affect their viability.

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ACKNOWLEDGEMENT

In preparing a report such as this, the writer inevitably calls upon many people for assistance. I was no exception and I wish to publicly pay tribute to all who contributed in any way to the success of this effort, especially noting the following:

- Mr. F. J. Pearce - literature search, European visits, Symposium/Workshop, critique of report draft
- Mr. I. A. Cameron - Japanese visits, Symposium/Workshop
- Dr. W-K Lu - Japanese and Korean visits, Symposium/Workshop
- Mrs. J. Cox - organization of Symposium/Workshop
- Speakers/participants in the Symposium/Workshop
- Canadian company officials - interviews (Appendix 2)
- Foreign company officials - interviews (Appendix 3)
- Steering Committee members - for their support, especially Dr. R. Lee re European visits
- Technical Committee members - for their support in a number of ways, particularly at the Symposium/Workshop
- Mrs. K. Robertson - for typing much of the original draft and Steltech's contribution to the Symposium/Workshop
- Mrs. C. Johnston - for typing the final report and giving it its truly professional appearance.

My thanks to all of you, and to the many others who helped in so many ways.

APPENDIX 1

STRATEGIC STUDY CONSORTIUM

Table I A1: Consortium Membership

Company/Organization	Contact
Algoma Steel Corporation, Limited	Mr. T. Burgan
Canada Centre for Mineral and Energy Technology	Mr. M. C. Campbell
Canadian Carbonization Research Association	Mr. R. F. Engler
Canadian Liquid Air, Limited	Dr. R. Lee
Canadian Steel Industry Research Association	Mr. J. Cook/Mr. T. Burgan
Iron Ore Company of Canada, Limited	Mr. B. Chandra
Linde, Union Carbide Canada, Limited	Mr. D. W. Kirkwood
National Slag, Limited	Mr. K. Spencer
Ontario Hydro	Dr. C. J. Simpson
Stelco Inc.	Mr. J. D. Young
Union Gas, Limited	Mr. C. D. Slemin

Table II A1: Steering Committee

Member	Affiliation
Mr. M. C. Campbell, Chairman	CANMET
Mr. T. Burgan	Algoma Steel
Mr. J. Cook	QIT-Fer et Titane
Mr. R. F. Engler	Luscar Ltd
Dr. R. Lee	Canadian Liquid Air
Dr. P. Pint	Energy Research Labs, EMR
Dr. C. J. Simpson	Ontario Hydro
Mr. C. D. Slemin	Union Gas
Mr. J. D. Young	Stelco Inc.

Table III A1: Technical Committee

Member	Affiliation
Dr. S. Guzman	QIT - Fer et Titane
Mr. M. Khan	CCRA/Algoma Steel
Mr. D. T. Liang	CANMET
Mr. R. Reesor	Ontario Hydro
Mr. G. Reid	Stelco Inc.

APPENDIX 2

VISITS TO CANADIAN COMPANIES

Ontario Hydro 89 08 22

- Ms. L. Buja-Bijunas - Load Forecasts Supervisor, End-Use Forecasting
- Mr. D. T. Gardner - Assistant Economic Analyst
- Mr. M. M. Krpan - Senior Planning Engineer
- Mr. R. D. McKellar - Economist, Energy Economics
- Dr. C. J. Simpson - Metallurgist, Special Divisional Projects Department

Stelco Steel Company 89 08 23

- Mr. R. J. Milbourne - Vice President, Manufacturing

Luscar Limited 89 08 25

- Mr. R. F. Engler - Director, Technical Services

Crows Nest Resources Ltd. 89 08 28

- Mr. H. S. Stellmach - Manager, Marketing & Coal Technology

Esso Resources Canada Ltd 89 08 28

- Mr. D. E. Weckman - Business Development Coordinator

Ipsco Inc 89 08 29

- Mr. J. Russo - Vice President, General Manager Flat Rolled Division
- Mr. M. Kostic - Manager, Metallurgical Services

Agloma Steel Corporation 89 09 01

- Mr. G. S. Lucenti - Vice President, Manufacturing
- Mr. J. Sagle - Superintendent, Operations Technology (Coke and Iron)
- Mr. M. Khan - Research Consultant

Slater Industries Inc 89 09 05

- Mr. B. Bowman - Vice President, Operations

Linde, Union Carbide Canada Ltd 89 09 05

- Mr. D. W. Kirkwood - Manager, Technology and Research Centre

CANMET/EMR 89 09 07

- Mr. W. Cameron - Physical Scientist
- Dr. J. F. Gransden - Research Scientist
- Dr. S. A. Mikhail - Research Scientist
- Dr. J. T. Price - Head, Metallurgical Fuels Division
- Dr. J. M. Skeaff - Head, Pyrometallurgy Section
- Dr. P. Pint - Acting Manager, Energy Diversification Research Laboratory
- Dr. A. H. Webster - Head, Physical Chemistry Section

Canadian Liquid Air Limited 89 09 07

- Mr. J. W. Coyle - Vice President, Corporate Development
- Dr. R. Lee - Director, Research and Technology

Sidbec-Dosco Inc 89 09 08

- Mr. L. Piperni - Director, Quality and Technology

QIT - Fer et Titane 89 09 08

- Mr. J. Cook - Manager, Process Metallurgy

Cape Breton Development Corp 89 09 11

- Mr. J. C. Campbell - Senior Research Engineer

Lake Ontario Steel Company 89 09 20

- Mr. S. Forrest - Senior Process Metallurgist
- Dr. R. Hadden - Vice President
  Quality, Service and Environment

Fording Coal Ltd 89 09 26

- Mr. M. Iliffe - Marketing Manager

Dofasco Steel Company 90 05 23

- Mr. H. Walker - Manager, Coke and Ironmaking

APPENDIX 3

VISITS TO INTERNATIONAL EXPERTS

1. Europe

British Steel Corporation 89 11 13
Teesside Laboratories

- Dr. R. B. Smith - Research Manager, Process Development
- Mr. M. J. Corbett - Head, Alternative Processes, Process Development Group
- Mr. J. O'Hanlon - Senior Consultant, British Steel Consultants
- Mr. J. Monson - Head, Energy and Coke Section
  Engineering and Ironmaking Division

Bergbauforschung 89 11 15

- Dr. W. Eisenhut - Division Manager, Cokemaking Division
- Dr. W. Rohde - Head, R&D Department, Cokemaking Division

Lurgi/Korf Lurgi Stahl Engineering 89 11 16

- Dr. F. Rose - Assistant Senior Manager, Metallurgy Division
  Ferrous Metallurgy Section, Lurgi
- Mr. M. Hirsch - Senior Manager, R&D Division
  Process Development Section, Lurgi
- Mr. B. Rollinger - President, Korf Lurgi Stahl Engineering GmbH
- Dr. W. Janke - Managing Director, Metallurgy Division

Klöckner Contracting and Technology (KCT) 89 11 17

- Dr. A. Hauck - Chief Metallurgist, Steelmaking Processes

HIsmelt Corporation Pty Limited 89 11 17

- Dr. D. K. Philp - General Manager, Process Metallurgy

MEFOS 89 11 20

- Mr. B. Berg - Managing Director
- Mr. N-O Lindfors - Head, Ironmaking/Oxygen Steelmaking Group
- Mr. P. Hahlin - Head, Measurement and Process Control Group

Swedish Steel Strip Products (SSAB) 89 11 21

- Mr. J-O Wikström - Manager, Ironmaking Research, Staff R&D
- Mr. N. Edberg - Manager, R&D Raw Materials and Blast Furnaces
- Mr. H. Petrini - General Manager, Coke Plant
- Mr. B. Gustavsson - Manager, Processtechnique

Deutsche Voest-Alpine Industrieanlagenbau GmbH (DVAI) 89 11 23

- Mr. F. Helten - Technical Sales
- Dr. W. Maschlanka - Director Technologies

Thyssen Stahl AG 89 11 24

- Dr. K. H. Peters - Works Manager
- Dr. K. H. Kreibich - Superintendent, Blast Furnaces

Ruhrkohle AG 89 11 24

- Dr. G. Nashan - Director of Ruhrkohle AG
- Dr. R. Kutzner - Manager, Quality Control
- Dr. K. Wessiepe - Manager, Production Planning
- Dr. W. Stewen - Manager, Coke Plant Engineering
- Dr. W. Rohde - Bergbauforschung

Hoogovens, Ijmuiden 89 11 27

- Dr. J. M. van Langen - Director, Research & Development
- Mr. M. te Lindert - Research Engineer, Coal and Coke
- Dr. M. Geerdes - Blast Furnace Technologist
- Dr. J. M. Driessen - Research Engineer, Blast Furnaces
- Mr. R. B. Vogel - Works Manager, Ironmaking

Centre de Recherches Métallurgiques (CRM) 89 11 28

- Mr. A. Poos - Deputy Director

ARBED 89 11 29

- Mr. F. Schleimer - Managing Director, Operations
- Dr. R. Henrion - Chef de Service, Service Produits
- Mr. G. Bernard - Paul Wurth SA, Vice President Engineering

Institut de Recherches de la Sidérurgie Française (IRSID) 89 11 29

- Mr. R. Nicolle - General Manager, Ironmaking
- Mr. Y. de Lassat de Pressigny - Raw Materials and Ironmaking Research

Visits to BSC, Bergbauforschung, Lurgi/KLSE, KCT, HIsmelt, MEFOS, and SSAB were by Mr. D. W. R. George, Steltech, and Mr. F. J. Pearce, Consultant. Visits to DVAI, Thyssen Stahl, Ruhrkohle, Hoogovens, CRM, ARBED, and IRSID were by Mr. D. W. R. George, Mr. F. J. Pearce, and Dr. R. Lee, Canadian Liquid Air.

2. Japan

Tohoku University 89 12 02

- Dr. Y. Omori - Professor and Director
- Dr. M. Tokuda - Professor and Head, Research Centre for New Metallurgical Resources
- Dr. R. Takahashi - Associate Professor
- Dr. Y. Shigeno - Metallurgist
- Dr. E. Kasai - Research Associate

Sumitomo Metal Industries Ltd 89 12 04
Kashima Works and Hazaki Research Centre

- Mr. Y. Kajiwara - Manager of Team, Project Promotion Department
- Dr. K. Nishioka - Manager, Ironmaking Research Laboratory
- Mr. M. Kojima - Manager, Ironmaking Control Section, Kashima Works
- Mr. T. Hirata - Senior Research Engineer
- Mr. T. Kawaguchi - Senior Research Engineer

Kawasaki Steel Corporation 89 12 05
Technical Research Division

- Dr. N. Ohashi - Senior Managing Director
  Director Technical Research Division
- Dr. T. Irie - Associate Director, Iron & Steel Research Laboratories
- Dr. K. Nakanishi - General Manager, Research Planning Department
- Dr. T. Nozaki - General Manager, Process Research Department
- Dr. T. Fukutake - Staff General Manager, Research Planning Department
- Mr. S. Taguchi - Chief of Ironmaking Laboratories, Process Research Department
- Mr. K. Takeda - Senior Researcher, Ironmaking Research Laboratory
- Dr. H. Itaya - Senior Research Engineer, Ironmaking Laboratory
- Mr. H. Marushima - Staff Engineer, Ironmaking Technology Section, Chiba Works
- Mr. H. Nishimura - Assistant Manager, Ironmaking Technology, Chiba Works

Japan Iron and Steel Federation (JISF) 89 12 06

- Mr. K. Kanamori - General Manager (NSC)
- Mr. T. Fukushima - Senior Manager for Smelting Reduction Technology (NKK)
- Mr. M. Yano - Senior Manager for Administration (NSC)
- Dr. I. Kobayashi - Manager for Prereduction (Kobe)

Kobe Steel Company

A. Head Office 89 12 07

- Dr. M. Ohtani - Technical Advisor
- Mr. M. Kitamura - Manager, Iron and Steel Technology Administration Dept

B. Iron and Steel Laboratories 89 12 08

- Dr. S. Ohta - General Manager, Iron and Steel Research Laboratories
- Mr. T. Uehara - Deputy General Manager, Technology Administration Dept
- Dr. S. Inaba - Manager, Ironmaking Research Laboratory
- Mr. S. Sasahara - Research Engineer, Ironmaking Research Laboratory
- Dr. T. Sugiyama - Senior Research Engineer, Ironmaking Research Laboratory
- Mr. T. Kamigo - Senior Researcher, Ironmaking Research Laboratory

C. Kakogawa Works - Ironmaking Department 89 12 11

- Mr. S. Tada - Manager, Ironmaking Technology Section
- Mr. K. Simomura - Engineer, Ironmaking Technology Section
- Mr. Y. Matsui - Engineer, Ironmaking Technology Section

Nippon Kokan KK

A. Tokyo Headquarters 89 12 12

- Mr. H. Uchibori - General Manager, Primary Technology Department
- Mr. Y. Yamaoka - Deputy General Manager, Iron and Steel Technology
- Mr. H. Yanaka - Assistant General Manager, Iron and Steelmaking Technology Development Department
- Dr. K. Yamada - Smelting Reduction R&D Team, Steel Research Center
- Mr. H. Mitsufuji - Senior Staff Researcher, Raw Materials and Ironmaking Laboratory

Note: Mr. Yamaoka is in charge of the oxygen blast furnace program and Mr. Yanaka is in charge of the smelting-reduction program.

B. Fukuyama Works 89 12 13

- Mr. S. Miyahara - Manager, Fukuyama Steelmaking Laboratory, No. 1 Process Research Department
- Mr. T. Sumigama - Chief Manager Ironmaking Technology, Ironmaking Department
- Mr. S. Nagano - Manager, Ironmaking Technology, Ironmaking Department
- Mr. M. Sakurai - Engineer, Ironmaking Department
- Mr. Y. Kawaguchi - Engineer, Ironmaking Department

Nippon Steel Corporation 89 12 15

A. R&D Laboratory III

- Dr. M. Sugata - General Manager, Ironmaking Technology Laboratory
- Prof. Y. Kawai - Executive Advisor
- Dr. T. Sugiyama - Senior Researcher
- Dr. K. Tamura - Senior Researcher (coal/oxygen blast furnace)
- Dr. H. Katayama - Senior Researcher (smelting-reduction)
- Mr. M. Ichida - Senior Researcher
- Mr. Y. Takamoto - Researcher (smelting-reduction)
- Mr. T. Arima - Researcher (formed coke)

B. Yawata Works

- Mr. T. Simizu - Group Manager, Technical Cooperation Division
- Mr. K. Inokuchi - Manager, Ironmaking Control Unit, Ironmaking Technology Department

All the visits in Japan were by Mr. I. A. Cameron, Steltech, and Dr. W-K Lu, Stelco Professor of Metallurgy, McMaster University.

3. Korea

Hanyang University 89 12 20

- various professors

POSCO 89 12 21 and 89 12 22
Research Institute of Industrial Science and Technology (RIST)

- Dr. D-H Baik - President of RIST (formerly Works Manager and Executive Vice President, POSCO)
- Dr. C-H Rhee - Vice President, Research
- Mr. I-O Lee - General Manager, Ironmaking Research
- Mr. Y-K Shin - General Manager, Steelmaking Research
- Mr. H-K Shin - Head, Raw Materials Laboratory
- Mr. C-M Cho - Head, Blast Furnace Laboratory
- Mr. S-S Lee - Chief Researcher (carbonization), Energy Research Laboratory

The visits in Korea were by Dr. W-K Lu.

4. The United States of America

AISI Direct Steelmaking 90 02 07

- Dr. E. Aukrust - Program Director (LTV)
- Mr. K. Downing - Manager, Pilot Plant (Inland)
- Dr. A. E. Morris - Visiting Professor
- Mr. J. A. McGinty - General Foreman, Pilot Plant
- Dr. P. J. Koros - Senior Research Consultant, LTV Steel Company

This visit was by Mr. D. W. R. George.